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Eos

SCIENCE NEWS BY AGU

Citing Indigenous Oral Teachings

How Do Zen Stones Float?

Earthquake Season on Mars

HARDWARE SOLUTIONS

SOMETIMES THE ANSWER TO THE QUESTION IS A SCREWDRIVER.

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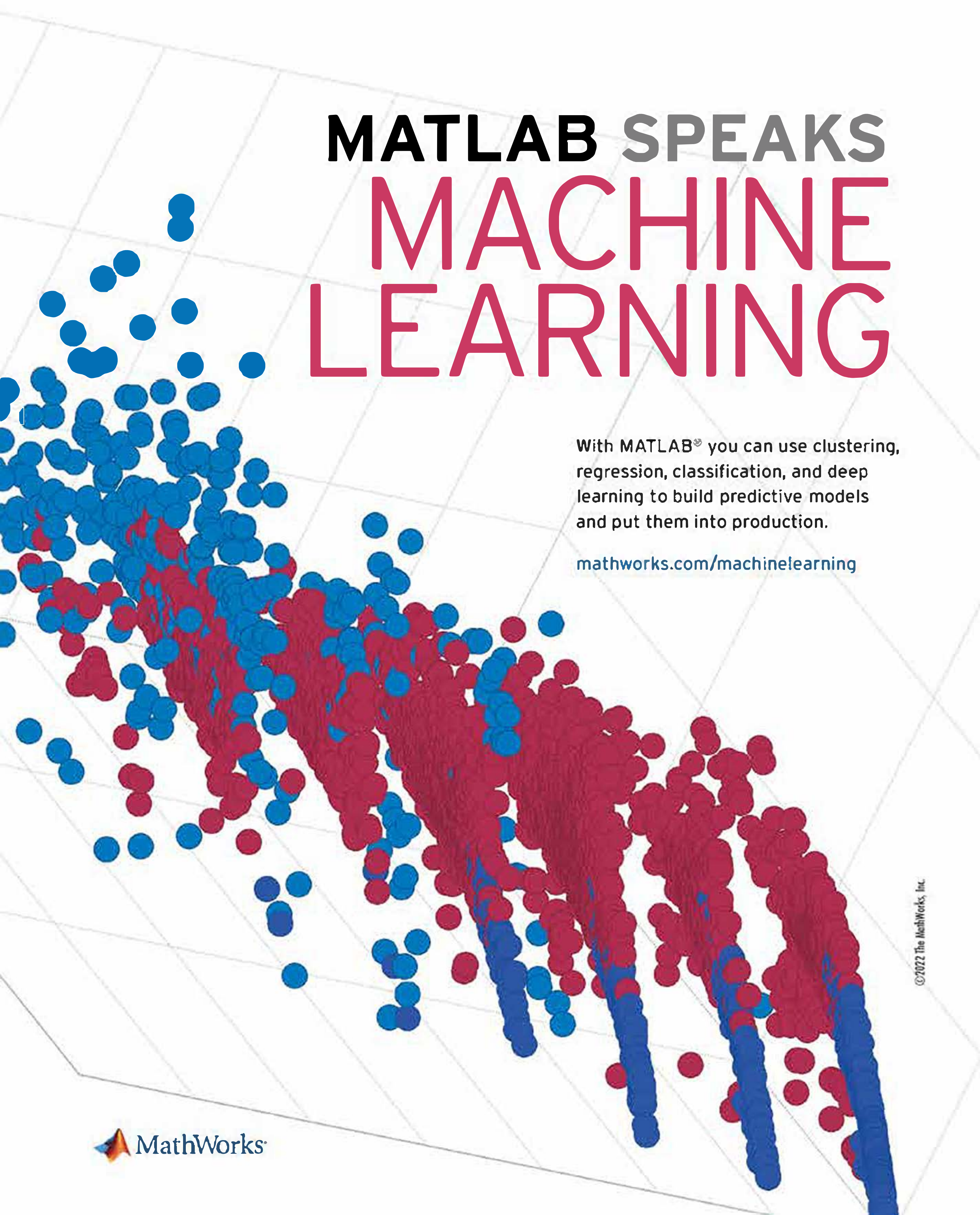
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Build It, and the Science Will Come

I promise, we didn't plan this entire issue just so I could write "Birds in backpacks doing science" in the table of contents—that was a lucky bonus. Clever theories, creative partnerships, and crunching numbers are all important parts of the scientific process, but sometimes you need to get down to the nuts and bolts. That's why this month in *Eos*, we highlight some of the innovative hardware solutions scientists are developing to get their research done.

We start with a feature by Collin P. Ward, who discusses how low-cost, energy-efficient light-emitting diodes (LEDs) are changing ocean research. Advanced LED technology can do a lot more than shed light on a subject; it can also provide wireless communication connecting fleets of autonomous research vehicles—and that's only the beginning. Turn to page 26 to read more about the wide array of benefits to science, including lowering the barrier for participation, that we could realize by embracing these sensors.

In our second feature, researchers describe the serious hardware needed to pursue new geodetic techniques rooted in quantum mechanics. On this month's cover, take a look at the strontium lattice optical clock operated by the National Metrology Institute of Germany. Optical clocks "have demonstrated at least a 100-fold improvement in accuracy over the usual atomic clocks," write Michel Van Camp and colleagues on page 32—read on to learn more about this and other cutting-edge technologies for measuring the shape, rotation, and gravity of our planet.

Finally, we get to science by the birds—cormorants, to be exact. Rachael A. Orben and colleagues write about the Cormorant Oceanography Project on page 38. They developed an advanced biologging tag technique that harnesses these coastal birds to take low-cost oceanographic measurements. The cormorants travel along the western coast of North America between British Columbia and Baja California, diving deep below the surface in pursuit of food. The tags were developed to have a negligible impact on the birds' behavior and use cell phone tech to transmit large amounts of data. Gathering observations from the cormorants could be one way to avoid the high cost of surveys from oceanographic vessels or autonomous underwater vehicles.

We also look at how portable hubs are making use of "Internet of Things" tech to help farmers and fishers in India (page 4), integrating echolocation into autonomous cars (page 18), and much more in this issue dedicated to the folks who, when faced with a problem, reach for a screwdriver.

Heather Goss, Editor in Chief

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Randy Fiser, Executive Director/CEO

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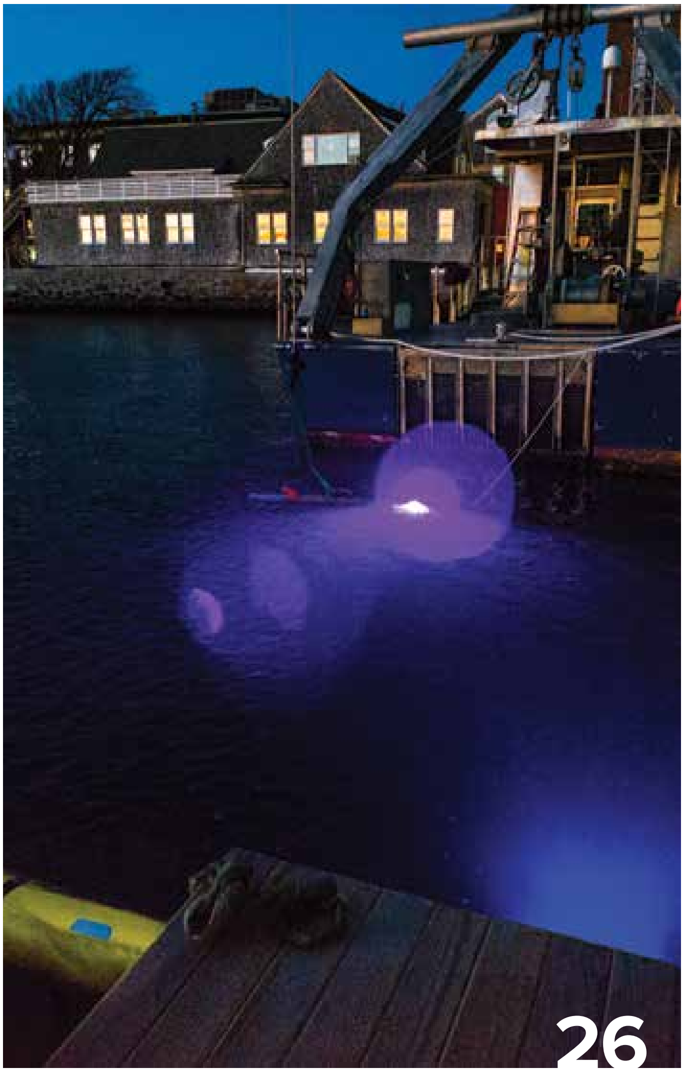

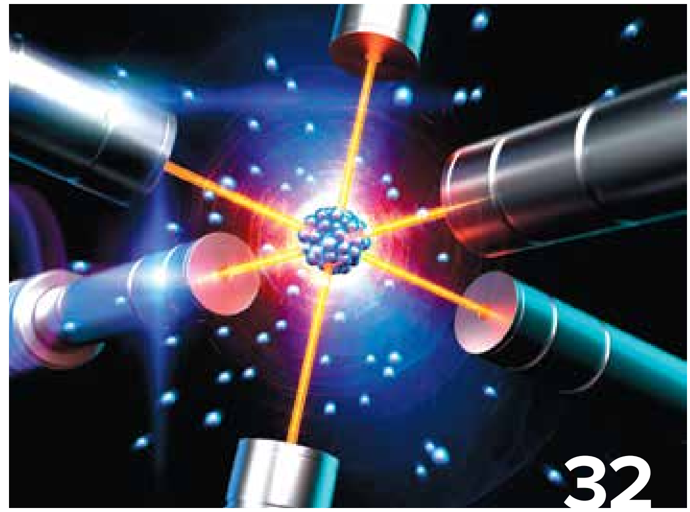

Features

On the Cover

The ultrahigh-vacuum chamber of an optical clock operated by the National Metrology Institute of Germany. Inside the chamber, strontium atoms are cooled by a laser. Credit: National Metrology Institute of Germany

Columns

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The "Internet of Things" Boosts Agricultural Livelihoods in India

Sensors and software applications embedded in everyday objects—the Internet of Things (IoT)—have brought tremendous benefits to rural villages and agriculture in India. But there are challenges in connectivity and infrastructure. Satellite-based networks can bridge the connectivity gap in remote areas but can be expensive because of the equipment required by both consumers and producers.

Narrowband (NB)-IoT technology may help bridge the gap between inaccessible areas and the benefits of Internet connectivity. As its name implies, NB-IoT uses a single, narrowband frequency (200 kilohertz), which limits transmission rates but allows many users to simultaneously connect over a wide area. The technology is low-cost for users and works on almost any mobile phone.

Improving Efficiency in Farming and Fishing

TV Prabhakar, principal research scientist in the Department of Electronic Systems Engineering at the Indian Institute of Science, Bangalore, noted that NB-IoT is fairly new technology, widely available within only the past several years. Prabhakar has published extensively on issues surrounding access to IoT devices.

Although NB-IoT is currently available only for commercial use, its accessibility will allow it to expand easily to consumers "because it is a technology that can work with traditional voice-only as well as [with] the evolution to 3G/4G/5G technologies," he explained.

NB-IoT works with existing satellites and mobile cellular networks, both of which are widely available in India. "Farmers and fishermen can use their mobile phones to receive and transmit messages, without any special skills," Prabhakar said.

For example, farmers monitor soil and crop health to ensure good yields, but this can be a labor-intensive effort. With NB-IoT technology and appropriate sensors, they can monitor such conditions as soil moisture, nitrogen, and phosphorus in real time through their phones.

"Farmers can receive alerts through the mobile application," said Prasanna Iyengar, director of products at Skylo, a tech start-up in the NB-IoT sector with deployment teams in India and the United States. They can then "use these alerts to take action such as turning on a water pump for irrigation. They can also decide the proportion of fertilizer based on the soil health care report."

The fisheries industry has also started making use of NB-IoT technology. Many fisherfolk in India still use traditional one-way shipboard radio, which works only up to about 20 nautical miles. With satellite-based NB-IoT technology, however, fisherfolk "can now venture out into the sea with the knowledge that in any distress situation, they are just an SOS away. The SOS is delivered by… platform connectivity to coast guards or nearby boats," said Iyengar. The service also allows them to receive timely weather alerts after they've left shore.

Innovation Hub

Skylo Hub is an easily portable, 20-centimeter block that transmits real-time data using NB-IoT. The breakthrough technology was launched in partnership with India's government-owned telecommunications provider, Bharat Sanchar Nigam Limited (BSNL), and is now bringing affordable satellite connectivity to remote areas around the country.

Skylo Hub integrates a digital satellite antenna and modem to establish a link with a satellite (owned by Inmarsat, a London-based mobile communications company); an IoT gateway that communicates with external sensors; and a modified NB-IoT chipset to gather and evaluate data from those sensors. It sends updates and alerts to a mobile app.

"The Hub is a plug-and-play integration, designed for the environment that you see outdoors in India—extreme heat, extreme cold, very heavy rainfall," said Iyengar.

Robin Bhawan Nakhawa, a Mumbai-based boat owner, opted for NB-IoT technology on

Skylo Hub provides a new way for fisherfolk to communicate safety conditions, fishing zones, and even prices using satellite technology. Credit: Skylo

one of his two boats. When the boat had an accident at sea that broke the propeller, the fisherfolk on board were able to notify him immediately through the NB-IoT platform.

"I sent my other boat and got the propeller repaired in 2 days," Nakhawa said. "Without [the] technology, the boat would have been stranded for many days."

Nakhawa said the technology also has helped his business in other ways. Rising ocean temperatures have changed the distribution of fish populations in the Indian Ocean, forcing fisherfolk to spend a lot of time searching for fish-rich regions. "We had to spend a lot on diesel [fuel] for the boat. But now with data on potential fishing zones...we can save time [and] money and improve our fish catch," said Nakhawa. Not only can they improve their catch, but also they can get more for it: The capability of alerting those on shore about the details of their catch while still far out at sea gives them more time and leverage in negotiating market prices.

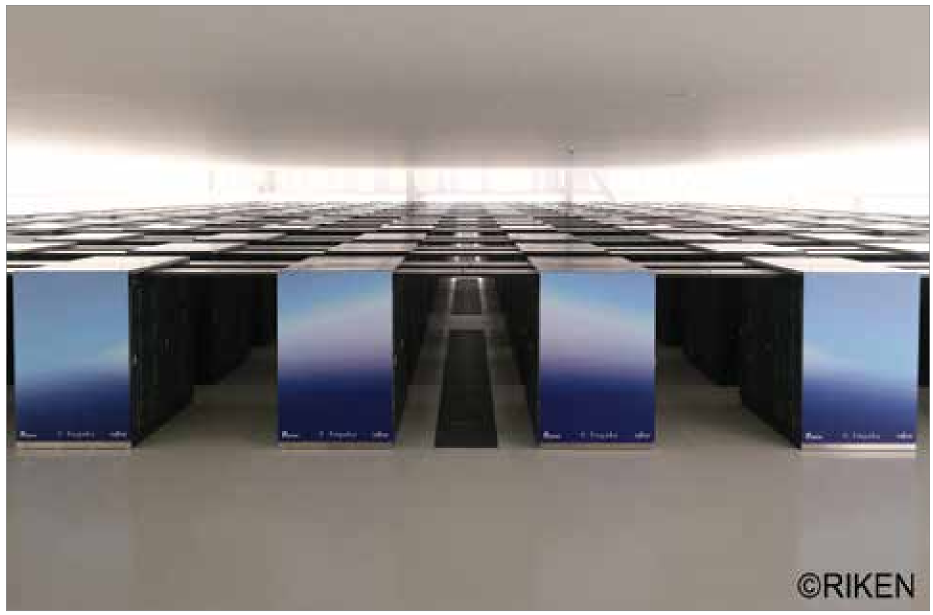
Fishermen who use Skylo's technology "can now venture out into the sea safely with the knowledge that in any distress situation, they are just an SOS away."

NB-IoT devices like Skylo Hub are part of a slowly expanding universe of technological efforts to bring greater access to real-time information to rural and other communities that lack reliable connectivity through relatively low cost setups. There are hurdles to the infrastructure: Cellular NB-IoT still needs to connect with an established network provider, so it is available now only in places where such a provider supports the technology.

A key limitation to expanding the scope of NB-IoT is that the technology allows for only small amounts of data to be transferred. It can be used only in devices supplying straightforward information such as location and cannot be used for video streaming or audio calls.

By **Deepa Padmanaban** (@deepa_padma), Science Writer

Accurate Simulation of Sun's Rotation Might Illuminate Solar Cycle



Researchers relied on the Fugaku supercomputer in Kobe, Japan, to help simulate the Sun's rotation. Credit: RIKEN Center for Computational Science

Japanese scientists said they have created the first accurate computer simulation of how the Sun rotates, reproducing a phenomenon in which its equatorial area spins faster than its polar regions. The insight could help explain the whys and hows of the solar cycle, one of the biggest mysteries of our star.

In a *Nature Astronomy* letter, the researchers described how they used a supercomputer named Fugaku, currently ranked the most powerful in the world, to re-create the Sun's more rapid equatorial rotation, something previous computer simulations were unable to achieve (bit.ly/fugaku-supercomp). Earlier attempts resulted in the poles rotating faster than the equator, but modeling the movement of 5.4 billion convection points inside the Sun did the trick.

"Our calculations indicate that the strong magnetic field generated by a small-scale dynamo has a significant impact on thermal convection," the researchers wrote. "The successful reproduction of the differential rotation, convection and magnetic field achieved in our calculation is an essential step to understanding the cause of the most basic nature of solar activity, specifically, the 11 yr cycle of sunspot activity."

From Helioscope to Supercomputer

The Sun is a giant ball of mostly hydrogen gas and plasma. Like Earth, it rotates on its axis, but its speed varies by latitude (as is the case with gas giants Jupiter and Saturn). Around the Sun's equator, the rotation period is about 25 days, whereas it's roughly 30 days near the poles. This differential rotation can be measured in several ways, including by observation of sunspot movement.

It was sunspots that provided one of the first clues that the Sun was in motion. Christoph Scheiner, a 17th-century Jesuit priest and astronomer, built an elaborate wooden projector called a helioscope to record sunspots and spent years logging their motions. On the basis of his observations in the 1630 book *Rosa Ursina,* Scheiner is credited with discovering differential solar rotation and bezing the first to measure the Sun's equatorial rotation, which he estimated to be 28 days.

In the centuries since then, scientists accumulated a detailed record of sunspot activity and studied its relationship to the solar cycle, the time it takes to reverse the

Sun's magnetic field, which is generated by the process of the solar dynamo. One goal of simulating the inner workings of the Sun is to understand how these processes work.

"The differential rotation is an essential ingredient of the solar dynamo, and thus we started researching it," said Hideyuki Hotta, an associate professor at Chiba University's Graduate School of Science and coauthor of the study. "The differential rotation is a large-scale flow but maintained by small-scale turbulence and the magnetic field. The complicated interaction between the large- and small-scale phenomena is worth studying."

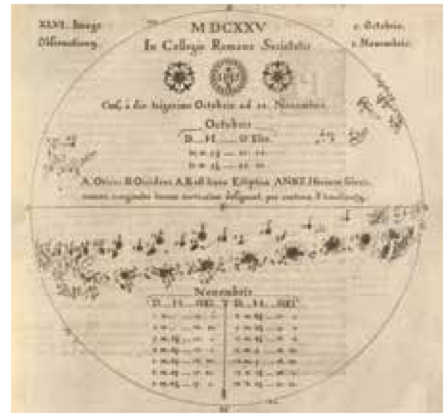
Simulations of the Sun's rotation didn't capture its peculiarities because they did not include turbulence, said Hotta. Prior to running the simulation, he believed that some unknown physics had to be involved, but it turned out to be a question of computing power and the experiment's resolution. The $1 billion supercomputer Fugaku, launched ahead of schedule in 2020 to help fight the COVID-19 pandemic, boasts 158,976 computing nodes and the ability to perform 442 quadrillion calculations per second; it also has been used to predict the flow of coronavirus particles and tsunami flooding. To simulate the Sun's interior and rotation, Hotta and coauthor Kanya Kusano, director of the Institute for Space-Earth Environmental Research at Nagoya University, ran their simulation on 41,472 cores for about 20 days. The results of the experiment included videos of the Sun's radial velocity and magnetic field.

"The differential rotation has large-scale shear, that is, flow speed difference, stretching and amplifying the magnetic field," said Hotta. "Our successful reproduction of the differential rotation can provide [the means to] more precisely follow the process. In addition, for the solar dynamo, turbulence in the solar convection zone is essential."

"Groundbreaking Discovery"

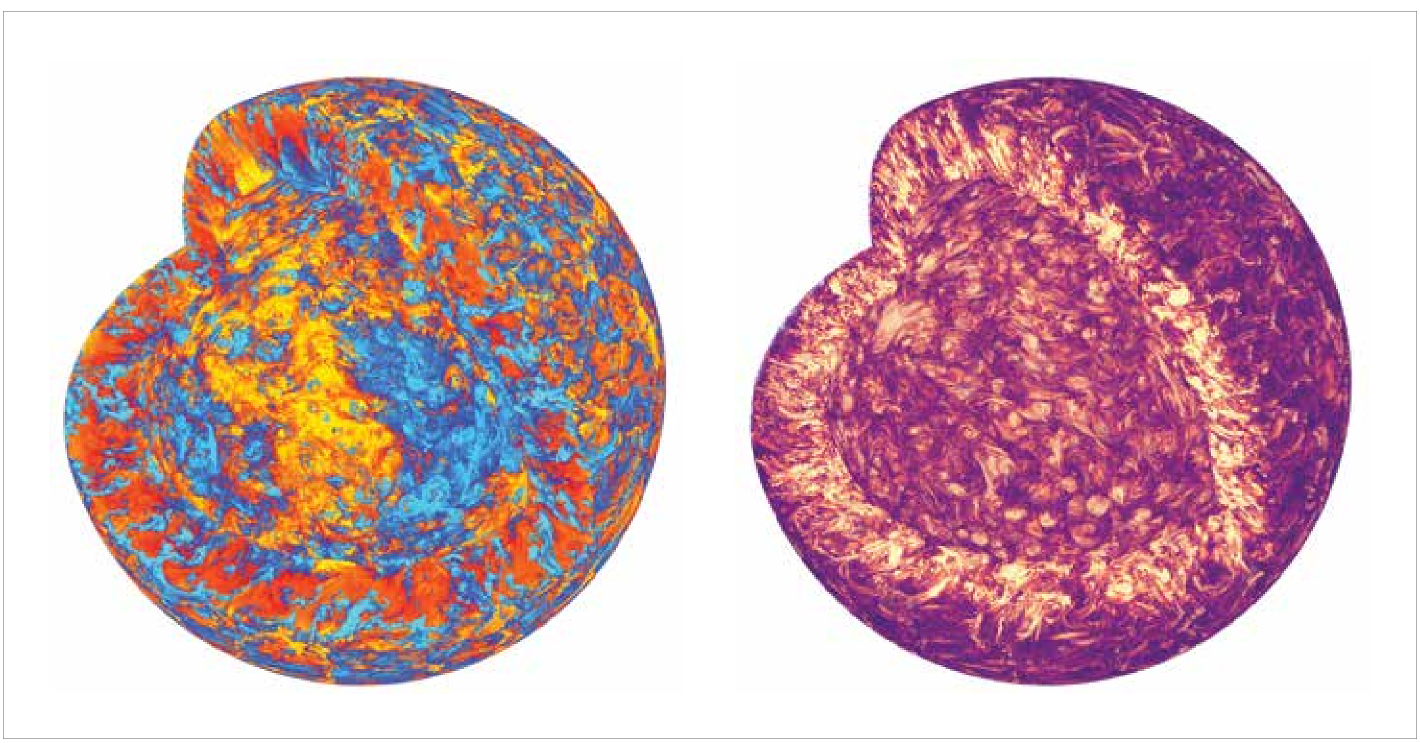
"Super-high-resolution computer simulations dig deep into the solar convection zone to reveal why the Sun's equator rotates faster than its poles; this is a groundbreaking discovery," said Mausumi Dikpati, a senior scientist at the High Altitude Observatory at the National Center for Atmospheric Research in Boulder, Colo., who was not involved in the study. "Understanding the physical foundation for simulating the Sun's differential rotation pattern and profile correctly is the first step toward simulating the 11-year solar cycle and its implication on space weather."

Hotta wants to further increase the resolution of simulations and include the Sun's surface, which he and Kusano simulated previously but without the rotation and magnetic field (bit.ly/Sun-simulations). Hotta believes a global simulation of the Sun including its deep interior may be possible to some extent on Fugaku. He also hopes that future results help improve predictions of the solar cycle, which began its latest phase in December 2019.



Shown here is a figure from the 17th-century book Rosa Ursina *by Renaissance scholar Christoph Scheiner, who used a helioscope to record sunspots.*

By **Tim Hornyak** (@robotopia), Science Writer



This graphic is a rendering of the entropy and magnetic field strength of the Sun, simulated by the Fugaku supercomputer. Credit: Chiba University

Academic Citations Evolve to Include Indigenous Oral Teachings

One tenet of scientific publishing is the use of academic citations—nods to what's known or has been done before. But referencing something other than a traditional written source can feel superficial: A "personal communication" citation, for example, typically doesn't show up in a reference list. Now, a librarian has spearheaded an effort to develop more thorough citation templates for the oral teachings often shared by members of Indigenous communities.

Written sources are definitely the norm when it comes to academic citations, said Lisa White, a paleontologist at the University of California, Berkeley and chair of AGU's Diversity and Inclusion Advisory Committee. But there's a need to be more inclusive, she said, and to recognize that a lot of knowledge, particularly that associated with Indigenous communities, is not recorded in written form. "There's a real rich history that a lot of Indigenous scholars bring."

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"Limitations in the Academic System"

Lorisia MacLeod, learning services librarian at Alberta Library in Edmonton, Alta., Canada, first realized there was a need for better citation tools for oral communication while studying anthropology as an undergraduate.

"There's a real rich history that a lot of Indigenous scholars bring."

Several of her professors repeatedly emphasized how difficult it was to properly acknowledge in their research the unrecorded oral teachings of Indigenous communities. They "drilled home the point that there were limitations in the academic system," MacLeod said.

For instance, personal communications typically don't appear in reference lists, said MacLeod. That's a significant drawback when scholars are taught to peruse reference lists to learn more about a subject, she said. "A personal communication that's not included in that list is just automatically not even recognized."

After earning a master's degree in library and information science, MacLeod, a member of the James Smith Cree Nation, started thinking that she could make a difference. "At a lot of institutions, the role of teaching citations tends to fall heavily on the librarians," she said. "It makes a lot of sense that there [should] be librarians taking a very active role in the future of citations."

Going Beyond Personal Communication

In 2018, MacLeod began developing citation templates for oral teachings. She relied on input from people associated with the Indigenous Student Centre at NorQuest College in Edmonton, where she was working at the time. The goal was to create templates that went beyond the abbreviated personal communication citation that was, at the time, the de facto way of referencing an oral source, said MacLeod. "There's a lot of information in these templates that doesn't exist in the original 'personal communication' version. It really allows us to be able to name our people in conjunction with their stories and the knowledge they were stewards of."

The templates, which are available online (bit.ly/templates-online), have options to include the name of the person being cited, their nation or community, where they live, and the subject of the communication, among other information. They're available for both American Psychological Association (APA) and Modern Language Association (MLA) citation styles, and MacLeod is committed to supporting people who wish to adapt the templates to other styles as well. These templates are currently in use by roughly 25 colleges and universities across Canada and the United States.

"It really allows us to be able to name our people in conjunction with their stories and the knowledge they were stewards of."

This work is important because most people in Western societies grow up receiving a Western education, said Nancy C. Maryboy (Cherokee/Navajo), president and executive director of the Indigenous Education Institute in Friday Harbor, Wash. "Very few people know what Indigenous science is." These templates give scholars the opportunity to present and acknowledge Indigenous ways of knowing, she said. "It's a way of leveling the playing ground to bring more awareness to Indigenous science."

By **Katherine Kornei** (@KatherineKornei), Science Writer

Supergreen Trees Can Signal Sites of Eruptions

In 2001 on Italy's Mount Etna, a thin line of pine trees started turning greener and greener, suggesting that they were photosynthesizing more than their neighbors were. The change was subtle enough that Sicilian hikers wouldn't have noticed a difference, but infrared satellites recorded the enhanced vegetation over two growing seasons.

The trees occupied a narrow band on the mountain, about 30 meters wide and 2 kilometers long. When Etna erupted along the same strip in November 2002, the trees were destroyed. Afterward, experts wondered whether the supergreen trees had predicted the flank eruption.

A team of researchers investigated the area around the eruption and found that volcanic steam may have saturated the soil, providing the roots with extra moisture and causing the pine trees to turn greener. The authors published their results in *Ecohydrology* and suggested that their findings could help pinpoint the outflow spot for future flank eruptions as well as reconstruct eruptions from the past (bit.ly/past-eruptions).

The Thin Green Line

As Europe's most active volcano, Etna is extensively studied and monitored. In 1973, Italian researchers poring over Skylab data noticed a line of enhanced vegetation. Months later, Etna erupted beneath those trees—just like what happened in 2001. The observations, published in 1975 (bit.ly/1974-etna), prompted the current research.

Nicolas Houlié, a geophysicist and a coauthor of the recent study, scoured satellite maps for more evidence of enhanced vegetation as part of his postdoctoral research. He found a line of greener trees on Etna from 2001 and 2002 and a similar line from 2001 on Mount Nyiragongo in the Democratic Republic of the Congo, which erupted a few months later.

To learn more about Etna's arboreal enigmas, Houlié and his colleagues collected tree cores with support from the Swiss National Science Foundation. They focused on surviving trees within 150 meters of the flank eruption. "It's very, very multidisciplinary work," Houlié said of the research team, which included experts in forestry, soil science, volcanology, biochemistry, and ecology. "It took us 3 days to find 20 trees we could agree on," he said, as each expert weighed in on the tree sizes, soils, and locations that affected the cores.

With samples in hand, the team moved to the lab. A biochemical analysis showed that carbon isotopes in the tree rings were similar for both the control period (1992–1996) and the eruptive period (1999–2003). The signal didn't match the expected values for deep-origin carbon, making carbon dioxide an unlikely influence. However, the oxygen-18 isotope dipped during the 2003 growing season, indicating the influence of volcanic water vapor in the soil. The authors speculated that the destroyed trees may have briefly benefited from volcanic steam saturating the soil.

Blasts of the Past

In theory, a scientist could check infrared satellite images for a line of greener-than-usual trees to see where rumbling volcanoes might erupt all around the world. But there's still uncertainty over what spurs the increase in photosynthesis. Volcanic vapor could cause the greening, as the study suggested, but lava could have altered the soil chemistry instead. "There's a very fine balance for lava flow to be beneficial for the trees," Houlié said.

"It took us 3 days to find 20 trees we could agree on," because each expert weighed in on the tree sizes, soils, and locations that affected the cores.

However, some experts said it is unlikely that enhanced vegetation will be useful for predicting future eruptions because a line of green trees does not occur on every volcano before every eruption. But "you should use everything that is available," said Erik Sturkell, a geophysicist at the University of Gothenburg who was not involved in the research. Greening trees are at least "a very good way to date previous eruptions in places where we do not have a historic record."

According to coauthor Paolo Cherubini, a dendrologist at the Swiss Federal Institute for Forest, Snow and Landscape Research, this study demonstrates that pre-eruptive volcanic activity influences tree chemistry, and any new volcanic indicator is useful. "To me, the most important thing is that oxygen-18 may be used as an indicator of past volcanic eruptions," Cherubini said. Isotopes could help reconstruct historic eruptions in places like Indonesia and Alaska, he said, where volcanoes are common but written records are scarce.

That's an intriguing prospect, Sturkell said. "It would be interesting to see the spatial distribution of this anomaly, if it dies out as you get further away." Researchers will need to test other theories to illuminate the volcanic processes causing trees to get greener. "One anomaly is good. Two is better, and especially if it's correlated to an eruption," Sturkell said.

By **J. Besl** (@J_Besl), Science Writer

In 2001 on Italy's Mount Etna, a thin line of pine trees started turning greener and greener, suggesting that they were photosynthesizing more than their neighbors. Credit: Alessandro Squassoni/Pixabay

Lasers Have the Makings of a 21st-Century Geoscience Tool

A laser may not be the first tool most geoscientists think to use when analyzing geological samples, but the technique known as laser-induced breakdown spectroscopy (LIBS) holds great potential for illuminating the geosciences.

"It's a very simple technique," said Russell Harmon, a geochemist at North Carolina State University who has used LIBS for decades.

By rapidly pulsing a high-powered laser at any given sample, a plasma is formed on the sample's surface and its atoms within are excited. As the atoms decay back to their ground state, they emit light at specific wavelengths, which can be spectrally analyzed to obtain a kind of geochemical fingerprint of the sample's atomic elements.

Because LIBS can capture the entire elemental composition of a sample, it is a versatile technique that can be readily applied in many different scientific domains. Over his career, Harmon has used LIBS in a variety of ways, including for evaluating environmental lead contamination, sussing out obsidian sources, and analyzing carbonates and silicates.

The speed and versatility of LIBS make it a "geochemical tool for the 21st century," according to Harmon and Giorgio S. Senesi, a researcher at the Italian National Research Council (CNR) (bit.ly/LIBS-21st-tool). It is capable of quantitative and qualitative analysis of the elemental composition of such materials as rocks, minerals, metals, sediments, soils, archaeological artifacts, gases, liquids, explosives, and beyond. It's also useful both in the laboratory and in the field, on Earth or off it.

"Today there isn't an area that LIBS hasn't been applied to by somebody," Harmon said.

Laser-induced breakdwon spectroscopy (LIBS) instruments are currently being used to explore the surface of Mars as part of SuperCam, which is aboard the NASA rover Perseverance. Credit: LANL

LIBS's Feats on Mars

Perhaps the most publicized uses of LIBS are out of this world, on Mars. Three LIBS instruments currently scour the surface of the Red Planet on three different rovers: ChemCam (Chemistry and Camera tool) aboard NASA's Curiosity; MarSCoDe (Mars Surface Composition Detector) on Zhurong, the first Chinese rover; and, most recent, SuperCam on NASA's Perseverance.

"It actually turns out [LIBS] is extremely adaptable for planetary science," said Roger Wiens, a planetary scientist at Los Alamos National Laboratory and project leader for the ChemCam and SuperCam instruments.

LIBS is able to analyze samples in near-real time with minimal preparation and handling. It is especially good at detecting lighter elements that most other techniques, like X-ray fluorescence, cannot pick up. For example, Curiosity's ChemCam was the first ground instrument to observe hydrogen on the surface of Mars and also found boron, a necessary component for RNA.

"Today there isn't an area that LIBS hasn't been applied to by somebody."

"LIBS is basically giving us information on almost all [of] the periodic table at once," Wiens said.

The technique also synergizes well with the other instruments on each rover, Wiens said. The powerful laser pulses hitting a sample produce something like a "very small version of lightning and thunder," creating "effectively a round ball of plasma" followed by a shock wave that conveniently removes dust from the material, allowing for cleaner experiments.

In addition to dust removal, LIBS produces a sound that can tell scientists something about the hardness of a material. Perseverance's SuperCam is outfitted with a microphone that listens to each shock wave as subsequent laser pulses burrow ever more deeply into the material being analyzed. This act changes the sound that is produced. Using the trend in changing sounds, researchers can figure out the hardness of a material.

"It's been a bit of a slower revolution, but a revolution nevertheless, in planetary science to start using this technique," Wiens said.

(Mostly) Limitless Possibilities

Although its possible applications seem countless, LIBS, like any technique, has its limitations. For one, LIBS is material-specific because the laser interacts differently with each material it contacts, so it is necessary to calibrate the instrument for each new material being measured.

"It becomes a real challenge to do quantitative LIBS for the Earth sciences community because there are generally not enough standards around to do that," Harmon said. So the spectral library for the materials often needs to be built.

Lewis Owen of North Carolina State University is using the SciAps Z-300 handheld LIBS instrument to analyze rock varnish on granite boulders in the Alabama Hills of east central California. Credit: Harmon and Senesi, 2021, https://doi.org/10.1016/j.apgeochem.2021.104929

This challenge arose on Mars—in the back of Perseverance is a set of 22 one-centimeter-diameter standard samples from Earth to calibrate the LIBS readings on Mars. There are also about 500 samples and a clone of the SuperCam LIBS instrument at the Los Alamos Lab to produce the spectral library.

Although there are hurdles to jump, LIBS could be used in future space missions to icy moons, asteroids, and elsewhere. The rapidity of LIBS has potential for gathering data from the extreme environment of Venus, a planet with intense heat and pressure that would quickly destroy most spacecraft. "LIBS is one of the best techniques to actually do on Venus because we could get a number of analyses in a short amount of time, beam the data back, and get [those] to Earth before the instrument caves in," Wiens said.

Back on Earth, with the commercial introduction of handheld LIBS units in 2016, the technique is more accessible than ever and is portable for fieldwork, Harmon said. About the size of a hair dryer, the handheld units are like "a box on a stick" with a tapered nose. According to Harmon, these affordable tools should be used by a younger generation of geoscientists to collaborate and find new and exciting ways to use LIBS. Building a diverse team and using LIBS to uncover new findings, on Earth and beyond, "that's a really powerful thing," Harmon said.

By **Richard J. Sima** (@richardsima), Science Writer

New Tool Crafts Fast, Free Flood Maps for the Global South

Floods are increasing in frequency and severity around the world. But despite the risk, few countries are learning from past floods to prepare for future ones.

That's largely due to a lack of data. Often, when a flood recedes, "there is no data set maintained nor lesson learned," said Hamid Mehmood, a project officer at the Institute of Water, Environment and Health at United Nations University. If a country maintains maps of its previous floods, the data are often outdated and undigitized. Worse, Mehmood said, 20% of countries have no flood maps at all. That places communities, economies, and supply chains at unnecessary risk.

To address the issue, Mehmood and his colleagues designed a program that capitalizes on cloud computing to make fast, free flood maps. Called the World Flood Mapping Tool, the program can display the extent of previous floods in less than a minute. That capability has benefits worldwide, but especially in the data-scarce countries of the Global South.

International Involvement

The World Flood Mapping Tool is a direct response to a lack of historic flood data, but it also capitalizes on improvements in computing power. Data sets previously took days to download; now, thanks to project partners Google and Mapbox, anyone with Internet access can use the tool.

The maps are built from NASA Landsat data and can re-create floods from 1985 to the present at a resolution of 30 meters. A user enters the dates of a significant past flood, and the tool shows how far the waters from that flood reached. That information can guide future evacuation routes, spotlight gaps in infrastructure, and inform future development.

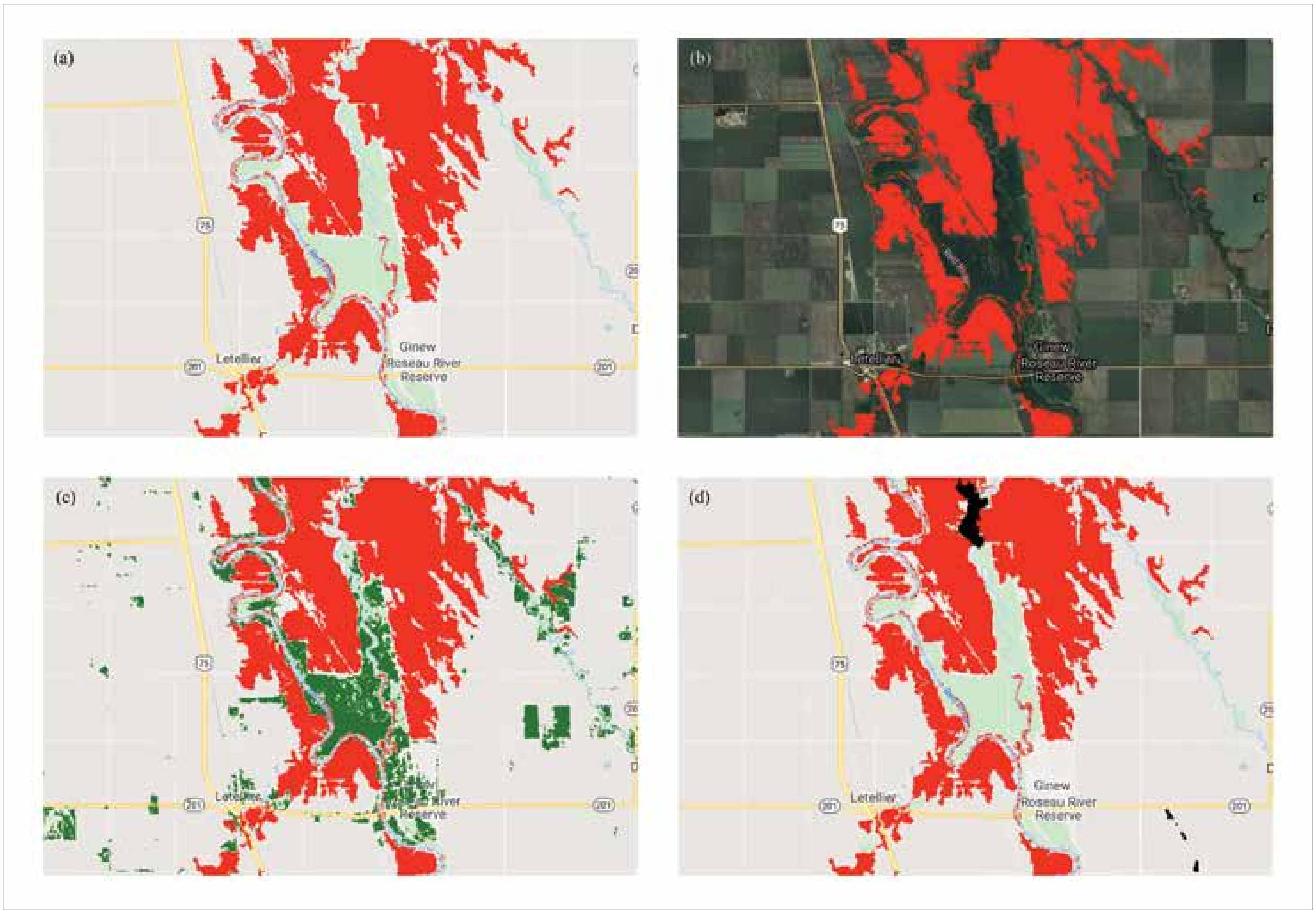
Importantly, the program accepts additional data sets from users. Users might overlay a demographics map to see where older populations live. A map of crop yields may show where floods threaten food security. The current version includes built-in population data and can color-code buildings with the highest number of residents.

The tool has worldwide applications, and dozens of international organizations informed its production. Stakeholders include disaster management agencies in Afghanistan, Myanmar, and South Sudan. Computing schools in Canada, Japan, and Qatar helped with model calibration. Planning and preparedness agencies in Kenya, Nepal, and Sri Lanka, among others, assisted with data validation.

Often, when a flood recedes, "there is no data set maintained nor lesson learned."

Those data partners provided maps of recently documented floods to test the tool's accuracy. A 2017 flood in Bangladesh damaged 89,030 hectares of ready-to-harvest rice; the tool determined the outlines of the flooded area with 83% accuracy. In Malawi and Mozambique, 2015 floods displaced 30,000 people and triggered a cholera outbreak. The mapping tool matched the flood zone with 85% accuracy. Across eight case studies—including floods in Australia, Chad, and Thailand—the tool displayed 82% mean accuracy.

Vietnam's Hương River flooded in 2020. A new mapping tool could help countries learn from past floods to prepare for future ones. Credit: Lê Minh Đức/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)



The World Flood Mapping Tool can produce historical flood maps at a 30-meter resolution in less than 1 minute. Here the tool maps the 2019 Red River flood around Winnipeg, Canada, showing different map layers: (a) vegetation marked on Google Maps, (b) vegetation marked in satellite imagery, (c) the normalized difference vegetation index (NDVI), common in remote sensing, and (d) the region's height above nearest drainage. Credit: Hamid Mehmood

International Applications

The tool is still developing, but even semi-accurate maps are an improvement in most regions.

Though flood forecasting has improved in Indonesia, for instance, the best data are still available in strategic areas like Jakarta on the island of Java, said Idham Moe, a hydraulic engineer with the Directorate General of Water Resources in Indonesia's Ministry of Public Works and Housing. Although millions of people live on Java, Indonesia has 6,000 inhabited islands; satellite observations would improve data management for the country's more remote regions.

The tool also cuts costs. Joash Bwambale is a water and irrigation engineer with Engineers Without Borders in Uganda. Mapping requires expensive equipment like ArcGIS, he said, and the resources to manage a network of remote sensors. "Forecasting is still a big challenge because we really don't have the systems in place," he said.

The World Flood Mapping Tool partly addresses those concerns, providing data-scarce countries with continuous monitoring to map flood risk. Those maps can then trickle down to local decisionmakers and individual farmers.

"[Flood mapping] is not an easy subject because of limitations with data," Bwambale said. "I think the biggest advantage of this tool for us who are in the South is to help us do reliable research that can easily inform the policymakers."

That matches Mehmood's goal for the project. "What we want to do is take the risk map down to a street level so local decisionmakers can invest in a certain bridge or a dyke," he said. Though that level of refinement isn't available yet, it's "coming up in the future," he said.

For now, the free tool is available to the public with a level of detail that distinguishes it from other flood risk prediction tools. Future updates will improve spatial and temporal accuracy and expand flood prediction functions. The team hopes users worldwide test the tool and provide their critiques.

"This is the first step," Mehmood said. "We understand that we need to improve the tool, and we are hoping for a lot of feedback from the community."

By **J. Besl** (@J_Besl), Science Writer

An Explanation, at Last, for Mysterious "Zen Stones"

Every once in a while, nature produces something with captivating fragility. Such is the case with Zen stones, which seemingly hover above frozen lakes, their masses supported by thin, sometimes nearly invisible, pedestals of ice. Researchers have now determined the physics underpinning the formation of Zen stones using laboratory experiments and numerical simulations. Sublimation of ice plays a key role, the team discovered, which puts Zen stones in rare company with other sublimation-sculpted natural features such as penitentes.

The best place to find Zen stones is on Siberia's Lake Baikal, where it's consistently cold and dry in the wintertime and the lake's surface freezes. But they're hardly commonplace, said team member Nicolas Taberlet, a physicist at the University of Lyon in France. "Even on Lake Baikal, they're rare."

Unexplained Beauty

In recent years, Zen stones have been popularized by nature photographers. Olga Zima, a photographer from Siberia, captured an image of a Zen stone on Lake Baikal that took top honors in a recent "Best of Russia" photo competition. This shot evokes a sense of calm, she said. "It symbolizes the balance of nature."

Despite the beauty of Zen stones, a convincing explanation of their formation has remained elusive. Theories abound on personal websites and blogs, but those ideas represent mostly guesswork, said Jeff Moore, a planetary geologist at NASA Ames Research Center in Moffett Field, Calif., not involved in the research. "It was idle speculation."

"The ice far from the rock disappears, and the rock itself protects the ice directly underneath."

In particular, one long-standing idea has been that Zen stones form when the ice around them melts. But that notion doesn't make sense, said Moore, because meltwater would likely destabilize the fragile structures. "Running water will tend to undermine the pedestal."

In 2017, Taberlet and his colleague Nicolas Plihon, a physicist at the French National Centre for Scientific Research, began reproducing Zen stones in the laboratory. Their motivation was a desire to explain a rare natural formation, said Taberlet. "It's mostly for the beauty of understanding something interesting."

Zen in the Laboratory

The researchers placed a metal disk 30 millimeters in diameter—simulating a stone—atop a block of ice. Taberlet and Plihon then enclosed the entire experimental setup in a freeze dryer, which functioned by pumping out air to reduce the humidity in its refrigerator-sized chamber and facilitate sublimation.

Taberlet and Plihon found that ice not covered by the disk sublimated at a rate of roughly 8–10 millimeters per day. The energy responsible for that sublimation came from the nearly uniform infrared radiation originally emitted by the freeze dryer's outer walls, which were at room temperature, the team concluded. A similar process is at work in nature, Taberlet and Plihon suggested, because significant cloud cover over Lake Baikal in winter tends to scatter sunlight, reducing its directionality.

The ice directly beneath the disk sublimated less rapidly, resulting in the formation of pedestals like those characteristic of Zen stones in nature, the researchers found. Taberlet and Plihon concluded that the rocks that top Zen stones function like miniature umbrellas, shielding the ice beneath them from infrared radiation and thereby lowering the rate of sublimation. "The ice far from the rock disappears, and the rock itself protects the ice directly underneath," said Taberlet.

To explain another feature of Zen stones—the characteristic depressions that persist directly beneath the rocks and are influenced by their shapes—the researchers turned to numerical modeling. They showed that these depressions can be explained by the far-infrared emission of the rock itself. That energy is responsible for a localized uptick in the sublimation rate in the immediate vicinity of the rock, the team proposed.

The research was published in the *Proceedings of the National Academies of Sciences of the United States of America* in October 2021 (bit.ly/zen-stones).

A Zen stone balances on a thin leg of ice atop Siberia's Lake Baikal. Credit: Maria Mosyagina/Shutterstock

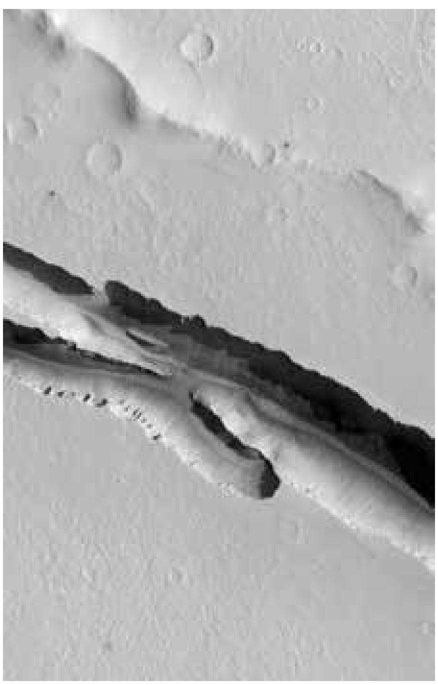
In the future, Taberlet and Plihon hope to study in more detail how Zen stones form in their natural environment. They'd like to place rocks on the frozen surface of Lake Baikal and film the formation of Zen stones over several weeks. Seeing these features grow in nature would be logical follow-up, said Taberlet. "That'd be the next step."

By **Katherine Kornei** (@KatherineKornei), Science Writer

Summer Could Be Earthquake Season on Mars

A new analysis of seismic data from NASA's InSight mission suggested that Mars could have an earthquake season. Researchers observed that certain kinds of marsquakes became more frequent beginning in the northern spring, with a peak in the summer.

"We are really convinced that there is a season of seismic activity," said Martin Knapmeyer of the German Aerospace Center, who was part of the multinational team that carried out the analysis. The seasonal changes the researchers found are best explained by annual changes in carbon dioxide (CO_2) ice load, illumination, or the annual solar tide. Tidal forcing by Mars's moon Phobos—which had previously been hypothesized to drive marsquakes—could not explain the seasonal pattern in the data.



It's thought that high-frequency marsquakes might originate in the Cerberus Fossae region of the planet. New results show that these quakes likely come and go seasonally. Credit: NASA/JPL/University of Arizona

Seismicity in the Solar System

Seismic activity on Earth isn't perfectly random, but it isn't thought to vary with the seasons except in certain places like Nepal, where heavy rains during the summer monsoon load rocks with water and make quakes less likely. Generally, earthquakes are assumed to be scattered mostly randomly through time, with the number of quakes above a certain magnitude expected to occur within a certain period given by a formula called the Gutenberg-Richter law. But other worlds play by different geological rules.

On the Moon, tremors mostly follow a monthly cycle. As it orbits Earth, the Moon experiences tidal forces, thanks to Earth's gravity. These tidal forces are thought to be a major driver of lunar seismicity, and data from lunar seismometers installed during the Apollo missions confirmed that moonquakes are driven by the tides.

Before the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander touched down on Elysium Planitia in 2018, researchers mostly assumed that marsquakes would behave like earthquakes—that is, they would occur mostly randomly and follow the Gutenberg-Richter law. But by 2020, the InSight team began to suspect there might be some seasonal or other time variation in the rate of high-frequency marsquakes, which are the most common type.

"High-frequency events have just been part of the puzzle of what are we seeing on Mars," said planetary geologist and InSight deputy principal investigator Suzanne Smrekar of the Jet Propulsion Laboratory, who was not involved in the newer study. "There have been a lot of hypotheses put forward within the team."

Explaining a Summer of Marsquakes

To investigate possible drivers of seasonal seismicity, the researchers began by ruling out the possibility that the uptick in marsquake activity they saw during the summer reflected changes to the InSight instrument settings or seasonal changes in the amount of seismic noise caused by wind.

Confident that their signal was real, the researchers tested how well different marsquake-driving mechanisms could explain the data. Variations in marsquake activity didn't follow Phobos's orbit, meaning that it is unlikely that the moon is driving the high-frequency marsquakes. Instead, the summertime burst in marsquake activity corresponded well to what scientists would have expected if seasonal tidal forces from the Sun or changes in the amount of CO_2 ice loading were driving the quakes. The modeling results also noted that variations in sunlight through the year corresponded with variations in quakes, suggesting that seasonal variations in sunlight could contribute to the summer marsquake season, but the researchers don't yet fully understand the relationship.

> **"We are really convinced that there is a seasonal variation in the seismic activity on Mars."**

"All three [explanations] are feasible," said Knapmeyer.

A Fluke Year?

The 520-day period Knapmeyer and his colleagues considered was only about 75% of a Martian year and lacked winter observations. However, high-frequency marsquakes had stopped occurring altogether by the Martian winter, so having a full year of data wouldn't have made a difference, said Knapmeyer.

"It was clear that during the rest of this year there wouldn't be any [high-frequency marsquake] detections anyway," he said. "So one could call it a day, so to speak, and run the analysis."

The next step in studying the phenomenon, both Knapmeyer and Smrekar said, is to see whether future years of marsquake data correspond with the seasonality predictions put forward in this paper. "They've made a good case...but I wouldn't say it's 100% locked down that it is, in fact, seasonal," said Smrekar. The study's authors also acknowledged that it's possible the marsquake burst observed was a fluke.

Knapmeyer said that efforts to look for seasonality over multiple years of InSight data are underway. "Currently, the second [seasonal] cycle is going on," he said, and the new observations correspond well to what would be expected if marsquakes were, indeed, seasonal. "So we are really convinced that there is a seasonal variation in the seismic activity on Mars."

By **Elise Cutts** (@elisecutts), Science Writer

New Sensor Aids Rare Earth Extraction from Acid Mine Drainage

A protein sensor developed by researchers that glows green when it encounters the rare earth element terbium could spur progress toward rare earth element mining in acid mine drainage in the United States.

The tool is the first luminescence-based sensor to quantify terbium at extremely low levels in an acidic, complex environmental sample. If commercialized, it could equip prospectors with the ability to search out the economically important element in abandoned mine tailings.

Rare earth elements are essential components in wind turbines and electric vehicles. Technologies to mine low-grade sources of rare earths—such as coal by-products, electric waste, and mine effluents—are attracting federal research dollars in the United States.

"It's really a pretty simple method, and it has a sensitivity that is similar to the state of the art," said chemist Joseph Cotruvo at Pennsylvania State University, who developed the sensor with two others. The tool, which is still in research and development, performed as well as highly accurate laboratory instruments but would be faster and easier to operate.

"If the sensor can be mass-produced or reused, that would go a long way toward lowering the characterization costs for domestic rare earth production," said Scott Crawford, a contractor for the National Energy Technology Laboratory (NETL) in Pittsburgh who was not involved in the development of the sensor. Increasing rare earth production in the United States is crucial to the country's economic, environmental, and national security, he said.

"It's really a pretty simple method, and it has a sensitivity that is similar to the state of the art."

Other researchers are also developing novel ways to sense rare earths. Researchers from NETL have tested fiber-optic sensors in liquid, and scientists at Idaho National Laboratory are working on a sensor using luminescent detection.

Illuminating Terbium

The new sensor comes from a protein discovered in the bacterium *Methylorubrum extorquens,* which lives in soils, on plants, and in other environments. The sensor could be used as part of a device to alert field technicians when terbium appears in acid mine drainage.

The protein lanmodulin selectively detects terbium, even in the presence of other rare earths or heavy metals dissolved in a solution. The researchers used tryptophan, a photosensitizer that absorbs light more efficiently than terbium, to transfer energy to terbium to excite it. Terbium then emits light at several wavelengths, the most intense being a greenish light at 545 nanometers. The luminescence grows more intense with more terbium present.

The sensor worked well when tested on acid mine drainage from the Lower Kittanning coal seam, even with low levels of terbium (on the order of parts per billion), a highly acidic solution, and in the presence of high concentrations of other rare earths and heavy metals.

The discovery was "really exciting, because terbium is actually one of the most valuable rare earths, and it's been deemed one of the five rare earths that are most economically critical," said lead author Emily Featherson, a chemistry doctoral candidate at Pennsylvania State University. The team published its results in the *Journal of the American Chemical Society* (bit.ly/terbium-quantification).

"Terbium is actually one of the most valuable rare earths, and it's been deemed one of the five rare earths that are most economically critical."

"This work represents a significant advancement in the field of rare earth detection," said Crawford. "The sensor must be extraordinarily selective, akin to finding the proverbial needle in a haystack, binding specifically to rare earths and not to other elements in the sample."

A limitation of the sensor is that metals must be in a liquid solution to be detected—

A stream in Pennsylvania is polluted with orange-tinted acid mine drainage. Credit: Rachel Brennan/Penn State

the ultraviolet (UV) light can get blocked by solids, said Cotruvo. He hoped the sensor will be fully developed within 5 years and engineered to detect other valuable rare earths as well.

From Waste to Revenue

Currently, the U.S. Department of Energy (DOE) is funding more than 30 projects to source rare earth elements from coal mining and its waste. Coal ash, refuse rock, young lignite coal, sludge, and acid mine drainage are treasure troves of rare earth elements, but the technology needed to extract the valuable materials has yet to hit the commercial market.

Acid mine drainage forms from the outflow of water from subsurface mines. Sulfur-bearing minerals in the rock turn water flowing by it acidic. In turn, the acidic water leaches heavy metals (including rare earths) from the rock. The highly corrosive water threatens aquatic life and water supplies.

Forty hard-rock mines in the United States produce 17–27 billion gallons of polluted water annually.

Forty hard-rock mines in the United States produce 17–27 billion gallons of polluted water annually, according to the environmental nonprofit Earthworks in 2013.

But converting the waste into revenue has become a priority of DOE and NETL. In a report to the U.S. Congress in 2017, the groups said that two coal and coal ash areas in the United States could supply millions of tonnes of rare earth elements, which is well above the domestic demand of 100,000 tonnes annually.

In recent years, China has produced and supplied an average of 90% of global rare earth elements, according to the U.S. Geological Survey. In 2019, the country threatened to curb supply during trade tensions with the Trump administration.

By **Jenessa Duncombe** (@jrdscience), Staff Writer

Satellites Allow Scientists to Dive into Milky Seas

For centuries, sailors have reported sightings of large patches of glowing oceans, stretching like snowfields from horizon to horizon. The ephemeral phenomenon, incidents of which can grow larger than some states, has long evaded close examination by scientists. But now, thanks to a little assistance from space, researchers may finally be able to dive into these milky seas.

Milky seas are associated with bioluminescence, light created by living organisms using biochemical triggers. Most well-known examples of bioluminescence are short-lived flashes, like those emitted by fireflies. But milky seas last for days or even weeks, a steady glow of light in the dark ocean visible only on moonless nights. Scientists suspect tiny, bioluminescent bacteria are responsible, but because glimpses of milky seas are so fleeting, researchers have had virtually no opportunity to examine the phenomenon directly.

Hunting for milky seas from space in near-real time may change that. Researchers using two NOAA satellites—the Suomi National Polar-orbiting Partnership (NPP) and the Joint Polar Satellite System (JPSS)—have developed the ability to quickly identify milky seas, opening the possibility of study before the glow disappears.

"Now we have a way of proactively identifying these candidate areas of milky seas," said Steve Miller, a senior research scientist at Colorado State University and lead author of the new study, which was published in *Scientific Reports* (bit.ly/milky-seas). "If we do have assets in the area, the assets could be forward-deployed in a SWAT-team-like response."

Rapid observations of the fleeting phenomena could help answer several lingering mysteries around milky seas, including how and why they form and why they are so rare.

"We really want to get out to one of these things and sample it and understand the structure," Miller said.

Turning On the Lights

Milky seas have been described by sailors for more than 200 years. Reports characterize them as having a pale glow, and travel through them is described as like moving across a snowfield or cloud tops. Ships' propellers create a dark wake as they move through the seas. The glow is so faint that moonlight renders it invisible to the human eye. The unusual waters seem more like the stuff of science fiction than science; indeed, they played a role in the Jules Verne novel *Twenty Thousand Leagues Under the Seas.*

Scientists experienced the spectacle only once, when R/V *Lima* chanced upon glowing waters in the Arabian Sea in 1985. Water samples from the ship identified algae covered with the luminous bacteria *Vibrio harveyi,* leading scientists to hypothesize that milky seas are associated with large collections of organic material.

Small groups of *V. harveyi* and other similar bacteria lack the faint shimmer found in milky seas. But once the population grows massive enough, the bacteria switch on their luminescence by the process of quorum sensing. Each individual bacterium seeds the water with a chemical secretion known as an autoinducer. Only after the emissions reach a certain concentration do the bacteria begin to glow.

"You know when you see these lights that there are a lot of luminescent bacteria there," said Kenneth Nealson, who along with Woody Hastings identified the phenomenon in the 1960s and was not a part of the new study. Nealson, a professor emeritus at the University of Southern California, estimated it would take around 10 million bacteria per milliliter of water to turn on the lights.

Gathering so many bacteria in one part of the ocean requires a significant source of food, and scientists suspect the bacteria are feasting on the remains of massive algal blooms. "If you give them something good to eat, they'll double about every half hour," Nealson said. "It doesn't take more than a day for them to have well over 10 million per milliliter."

Unlike algal blooms that drive phenomena like red tides, which are supposed to drive fish away, milky seas may be working to attract them. Fish eat the bacteria as well as the dying algae, and consumption doesn't end the bacteria's life cycle.

"For [the bacteria], the inside of a fish's stomach is a favorable environment," said Steve Haddock, a biologist at Monterey Bay Aquarium Research Institute in California and one of the authors of the new research. "They can live inside [a fish's] stomach just like bacteria live inside our bodies."

Seas from Space

This isn't Miller's first foray into using satellites to hunt for milky seas. After he and his colleagues questioned whether bioluminescent activity could be detected from space, Miller wondered what sort of ocean activity might be visible. He found a report from *Lima* that listed its coordinates and the date and time of the 3-day-long encounter. Using this information, he hunted through archival data collected by the U.S. Defense Meteorological Satellite Program constellation of satellites, a collection of polar-orbiting satellites surveying Earth in visible and near-infrared light. In 2005, he and Haddock, along with two other researchers, reported the first detection of a milky sea from space (bit.ly/first-milky-sea).

"It was really difficult to find that milky sea in that older generation of data," Miller said. He attributed the success to the clear records kept by *Lima*. "There was no way to pick it out on my own independently." It turned out that the ship had navigated through only a small part of the 15,400-square-kilometer glowing sea, which stretched to roughly the size of the state of Connecticut.

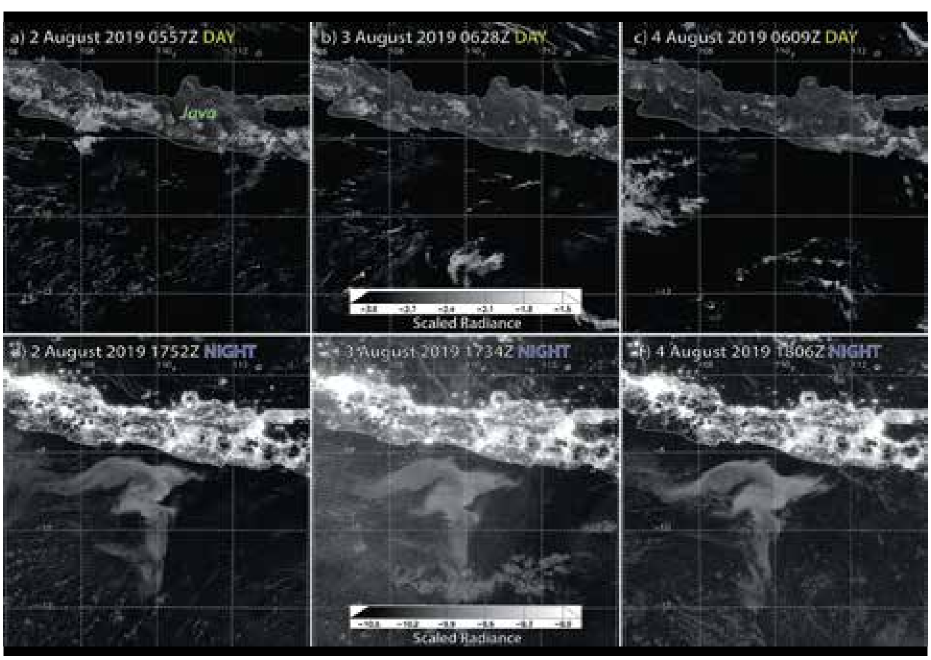
Encouraged by his success, Miller turned his attention to the newly launched Suomi NPP and its Day/Night Band (DNB) instrument, which breaks down light into gradients. Suomi NPP can sift through lights from cities, wildfires, and the atmospheric glow caused as ultraviolet light breaks apart molecules. Finding the faint light from milky seas required looking for dim seas and pulling out the short-lived events.

"It was a decade of learning," Miller said of the time spent culling transient events in search of milky seas.

After determining that most historical sightings of the glowing bacteria over the past 200 years occurred in the Indian Ocean and around Indonesia, researchers concentrated their hunt on that region. Moonlit nights were eliminated because they were too bright. Ultimately, Miller and his coauthors identified a dozen milky sea incidents between 2012 and 2021.

The largest milky sea satellite spotting occurred south of Java in 2009. The DNB detected a dimly lit sea on 26 July and continued to track it until 9 August, when the Moon once again drowned out the bacteria. Imagery confirmed that the luminescent sea spanned more than 100,000 square kilometers. Estimates place the number of bacteria involved in the event as exceeding 10 sextillion (a sextillion is 1,000 trillion), making it the largest event on record.

"This is just an inconceivable number of bacteria participating in that event," Haddock said.



This milky sea phenomenon covered nearly 100,000 square kilometers near Java, Indonesia. The bright patches on the island are city lights. Credit: Miller et al., 2021, https://doi.org/10.1038/s41598-021-94823-z, CC BY 4.0 (bit.ly/ccby4-0)

Satellite observations also allowed researchers to take stock of the conditions of the ocean when milky seas are present. The new research measured details like water temperature and the amount of chlorophyll present.

"There's no doubt that there's a connection between a high level of chlorophyll and milky seas," Nealson said. "Nobody's been closer to an answer for the phenomena than [Miller, Haddock, and their colleagues]; they did a really wonderful job."

Biologist Peter Herring, a retired professor at the National Oceanography Centre in Southampton, U.K., agreed. "Almost all of the information on milky seas up to the 1990s was anecdotal from people on ships," Herring said. "Now we have remote observations from satellites showing exactly where these phenomena are happening and how they change with time. That's a major step forward."

Diving into the Seas

Although satellite imagery is an important tool, Miller hopes that the project will eventually lead to real-time observations. There are a lot of unanswered questions about milky seas, some quite basic. For instance, scientists aren't sure whether the bacteria form a thin film on the surface or extend deeper into the water. Nor are they certain that algal blooms are the primary food source for the bacteria.

"If you were in the middle of one of these blooms, a lot of the things that we talk about would become obviously right or wrong," Nealson said. "That's very unusual in science, that you could get such a clear answer."

But real-time, in-person study may continue to prove elusive. There are no major ocean facilities near the region where milky seas seem to be most prevalent, and the seas are rife with pirates and other dangers that keep many research vessels away.

Nor have photos or videos ever reliably captured milky seas. The closest attempt was in 2010, when a crew tried to take a photo of the glowing sea using a flash, which promptly washed out the dim phenomenon. Miller hopes more commercial crews can be equipped with cameras specially designed to photograph bioluminescence.

In the meantime, Miller hopes to one day experience the fleeting mystery in person.

"I've always wanted to dive into a milky sea and see if it's still glowing under the surface," he said.

By **Nola Taylor Tillman** (@NolaTRedd), Science Writer

Deep-Ocean Cooling May Have Offset Global Warming Until 1990

Tracking ocean temperatures has long helped scientists measure Earth's accelerating energy imbalance, but researchers at the University of California, Santa Barbara have now applied new machine learning techniques to extrapolate deep-ocean temperatures (below 2,000 meters) with surprising results.

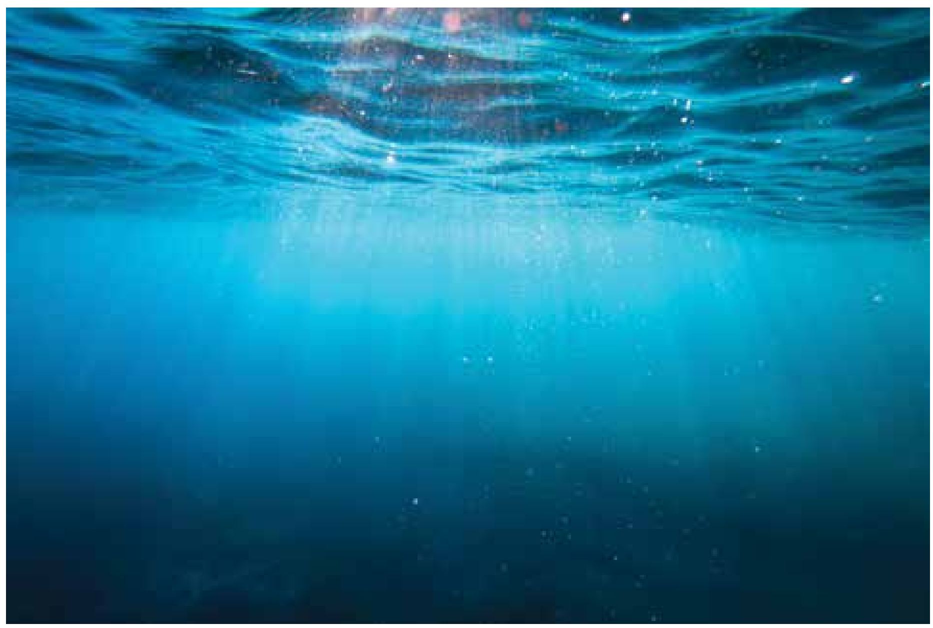
Whereas past research has shown gradual warming that has accelerated over time, new research from Aaron Bagnell, a doctoral student, and Tim DeVries, an associate professor, has suggested that cool deep-ocean temperatures offset surface warming until roughly 1990. After 1990, the authors posited, more rapid warming caused a spike in surface ocean temperatures that could not be offset by prior deep-ocean cooling.

"Previous methods might have just taken data from 1 year or 1 month, and applied some mapping algorithm to fill in the gaps, whereas we're considering the whole record all at once."

Cooling associated with past events like the Little Ice Age (which covered roughly the 14th–19th centuries) had a lingering effect; DeVries said it takes roughly 1,000 years for surface ocean waters to circulate to the deep ocean, and vice versa, meaning that those cooler waters had an impact even centuries later. After 1990, the cumulative impact of surface-level warming was enough to cause whole-ocean temperatures to rise. The study was published in *Nature Communications* (bit.ly/deep-ocean-energy).

Bagnell's autoregressive artificial neural network (ARANN) is an adaptation of a machine learning method that he said improves on previous methods of estimating past deep-ocean temperatures. Historically, sparse data from the deep ocean have made it difficult, if not impossible, to accurately extrapolate whole-ocean temperatures. "Previous methods might have just taken data from 1 year or 1 month and applied some mapping algorithm to fill in the gaps, whereas we're considering the whole record all at once, and we're letting this machine learning algorithm, or artificial intelligence algorithm, make connections between… what happens near the surface [and] what happens deeper down," DeVries said.

With machine learning techniques, each data point can be influenced by every other data point in a way that accounts for the ocean's dynamic properties. "So, in principle, the machine learning technique is learning how to adapt the relationships that it sees near the surface," from around the present to prior time periods, as well as [in] deeper parts of the ocean, Bagnell said.



Unsplash/Cristian Palmer

Accounting for Sea Level Rise

The result is a finding that not everyone agreed with. Greg Johnson, an oceanographer with NOAA's Pacific Marine Environmental Laboratory, said the lack of data about deep-ocean temperatures prior to 1970 made him skeptical about the potential accuracy of these findings. He also pointed to rising sea levels as evidence that global warming was proceeding steadily prior to 1990.

"The sea level has been going up fairly steadily…. From the 1990s to the 2000s and 2010s, it's definitely accelerated considerably, but prior to that it was still rising globally, and that's probably not all ice melt, which is what you'd have to conclude from this study," he said, pointing to a global rise in sea surface temperatures over the study's time frame.

Bagnell responded that data on sea level rise don't necessarily contradict his findings: "Thermal expansion of the oceans due to warming accounts for roughly one third of the sea level rise observed today. The other two thirds is mainly due to the addition of fresh water from land sources like melting glaciers. In addition, the historical record of tide gauges and satellites (for 1993 onward) indicates that sea level rise has been accelerating from the 20th century into the 21st century, meaning sea levels likely weren't rising as rapidly then as they are today. So the possibility that freshwater input accounted for a larger fraction of sea level rise during the 20th century isn't out of the question."

By **Robin Donovan** (@RobinKD), Science Writer

Autonomous Vehicles Could Benefit from Nature

Autonomous vehicles are jauntily steering through the streets of more and more cities, but the navigation systems in these vehicles remain an evolving technological concept. As companies vie for the rights to urban terrains, they typically use sensors based on optical properties or radio waves to map and navigate the environment. These options may not provide the best coverage, especially in bad weather. A team of researchers at the University of Michigan has turned to nature to develop something better.

"Animals have the amazing ability to find their way using sound," said Bogdan Popa, an assistant professor of mechanical engineering at the university and principal investigator on the project. "We want to develop a sensor that uses sound like animals."

Previous efforts with sound have failed because sound waves do not travel as far in air as light and radio waves do. In fact, current ultrasound sensors have a range of only 1 meter and produce low-resolution maps.

Popa plans to leverage knowledge from nature to advance this technology.

Dolphins, bats, and whales use echolocation, a technique in which a sound pulse is emitted into the environment. When the pulse encounters an object, it bounces off and sends reflections back to the animal to decipher. Using this approach, animals can navigate their terrain, find food, and avoid predators—all of which happens very quickly.

Popa believes echolocation offers a tantalizing new opportunity that will allow autonomous vehicles to operate in an uncertain world under inclement weather conditions while retaining their autonomy.

The Sensor of the Future

Sound has a limited range as it travels through air. To propel sound waves more efficiently, Popa and his team constructed an acoustic lens using passive and active metamaterials.

Similar to an optical lens, the acoustic lens consists of two engineered pieces of patterned plastic that are capable of focusing ultrasonic sound waves (35–45 kilohertz) in any desired direction with only the slightest deformation. This capability means that the lens can be fixed to the vehicle and does not need to be cleaned or realigned. With only minor adjustments, the lens can project a focused wave in almost any direction. Popa likened this new sensor to a laser beam compared with traditional sound applications that are more like an incandescent lightbulb.

The team also developed a process to analyze the vast amount of information contained in the returning echoes. To do this, they made the project even more multidisciplinary, turning to computer science to interpret biological sensory signals. The Michigan team developed a convolutional neural network, consisting of individual deep learning algorithms that can differentiate, weigh, and assign importance to self-labeled images.

"Using some experiments with dolphins to understand their behavior, we developed a series of neural networks," said Popa. "Each neural network is specialized to recognize one object, like a type of fish, a threat, rocks, etc."

For the first stage of the study, the team plans to develop a series of neural networks. Each network will be trained to interpret the returning echoes for a specific object and determine whether the object is present in the environment and its likeliest position.

"This is a modular approach that is more decentralized," said Popa. "It is easier to do as opposed to one algorithm that has to provide all the data."

Once identified, the object will be placed on the map in front of the vehicle. Popa plans to simultaneously map the environment with multiple neural networks to identify many different objects to re-create the world before the vehicle.

Next Steps

Once a network is trained, Popa believes it will be able to provide an answer to questions about location almost instantaneously. The team plans to layer neural network after neural network to provide the power of interpretation for an array of incoming echoes.

Although the researchers are still acquiring the data to train the various algorithms in the neural networks, they plan to test the system using virtual simulations. If all goes well, they will release the new acoustic sensor-based navigation system into the real world to see how it helps autonomous vehicles navigate the streets.

"Since this technology is still in the beginning stages, it's hard to say how it will compare with current sensors," said Teddy Ort, a Ph.D. candidate in the Computer Science and Artificial Intelligence Laboratory at the Massachusetts Institute of Technology. "If it could provide detailed 3D data at range, it could prove very valuable not only to replace but perhaps to augment the current sensor suites." Ort did not contribute to this study.

As the demand for autonomous vehicle technology increases, Popa's contribution could improve the safety of vehicles navigating every community, large and small.

"For me, the most exciting part is understanding how the natural world does what it does in such an efficient way," said Popa. "We hope to replicate or equal the performance of these biological systems."

Researchers explored convolutional neural networks during dolphin trials at the Dolphin Quest facility in Hawaii. This work is also being used to test some of the CNN-based algorithms developed during the project. Credit: Bogdan Popa

By **Stacy Kish** (@StacyWKish), Science Writer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Sediment Mismanagement Puts Reservoirs and Ecosystems at Risk

Dams store water flowing down rivers and streams in reservoirs, providing protection from floods. Dams also serve as sources of electrical power, and they provide water for domestic and irrigation uses and flat-water recreation. By design and default, most dams in the United States also store sediment, indefinitely.

Sediment accumulation behind U.S. dams has drastically reduced the total storage capacity of reservoirs. Sedimentation is estimated to have reduced the absolute water storage capacity of U.S. reservoirs by 10%–35%. Consequently, on a per capita basis, the water storage capacity of U.S. reservoirs today is about what it was in the 1940s and 1950s, despite there being more dams [*Randle et al.*, 2019]. This comes as no surprise: More than 40 years ago, D. C. Bondurant warned, "It must be recognized, that with few exceptions, ultimate filling of reservoirs is inevitable" [*Vanoni*, 1975].

At the same time, reaches downstream of dams have been deprived of sediment, resulting in declines in the health of habitats and organisms [*Ligon et al.*, 1995]. After rivers and streams deposit their sediments into reservoirs, the remaining clear water is more effective at moving sediment in the channel downstream [*Kondolf*, 1997]. High-energy "hungry water" releases erode downstream channel beds and banks, leading to incised rivers [*Williams and Wolman*, 1984], accelerated beach erosion [*Dai et al.*, 2008], and oversimplified channels lacking critical habitat features such as backwaters, connected floodplains and wetlands, pools, riffles, and runs [*Kondolf and Swanson*, 1993].

Managing reservoir sediments in the United States has historically involved dredging, excavation, and removal of sediment to off-site locations. These approaches are expensive and do not restore sediment continuity with downstream river channels. Alternative management approaches have revealed that mobilizing and passing sediment through reservoirs to downstream reaches can maintain or restore both reservoir capacity and downstream ecosystems.

Here we present recommendations to address the escalating issue of sediment trapping in reservoirs. Without action, continuing accumulation of sediment in reservoirs will further reduce reservoir capacities, increase maintenance costs, reduce reservoir operational flexibility, and increase degradation of downstream environments. In rare cases that foretell what a future of sediment mismanagement might look like, failure to deal with captured sediments has led to catastrophic dam failure [*Tullos and Wang*, 2013].

Paonia Reservoir in northwestern Colorado, seen here in 2014, reached the end of its sediment design life after 50 years when the outlet (the boxlike structure to the right of the excavator), located at the top of a 21-meter tower, became clogged with sediment. Credit: U.S. Bureau of Reclamation

The Mechanics of Reservoir Sedimentation

Streamflows entering reservoirs are released downstream by way of intakes that are generally located well above the bed of the reservoir, either at the water's surface on towers or across a surface spillway along the length of the dam. Because sediment transported into a reservoir is heavier than water, it settles to the reservoir bed, reducing the storage space available for water. Many dams also have low-elevation outlets that allow for sediment flushing. These outlets are most common at diversion dams but also exist at many water storage dams, where they were constructed above their respective sediment storage pools. Continued sediment accumulation to reservoirs can either cover or compromise these low-level outlets.

Achieving sustainable reservoir management requires acknowledging that sediment is not a pollutant, but is, instead, like water, often a beneficial resource that must be wisely managed.

To prolong reservoir life and recover lost storage volume, low-level outlets or bypass tunnels may need to be constructed to direct newly inflowing or already accumulated sediment through or around a dam. Even with the high costs of modifying existing dams with such features, passing sediment through a reservoir is still less expensive over the life span of the reservoir than dredging and off-site storage [*Wang et al.*, 2018].

Frequent, small, and strategic releases of sediment, such as the one that occurs annually from the reservoir at Fall Creek Dam in Oregon (seen here) to support downstream fish passage, can minimize impacts of sediment management on ecosystems and other reservoir functions compared with infrequent releases of large sediment volumes. Credit: Desirée Tullos

Regulatory Obstacles

Efforts to mobilize and route sediment past dams are often delayed by regulatory requirements shaped by the long-standing—though misguided—belief that sediment always negatively affects water quality and increases risks to downstream communities. To increase the sustainability of reservoirs, sediment management regulations need modernizing, informed by the knowledge gained from years of scientific research and monitoring of reservoir and downstream river conditions.

Sediment management in the United States exists within a regulatory environment that is "ever changing and…[continuing] to grow in complexity," according to a report by the *International Commission on Large Dams* [2019]. Today discharging sediment downstream of a dam requires an individual, project-specific federal permit. The 2007 court case *Greenfield Mills v. Robert E. Carter Jr.* set the precedent for this requirement, establishing that the flushing of sediments is considered a "discharge of dredged material from a point source" and subjecting the practice to regulation under Section 404 of the Clean Water Act (CWA). In addition to federal regulations, sediment management operations often require authorization at the state or local level.

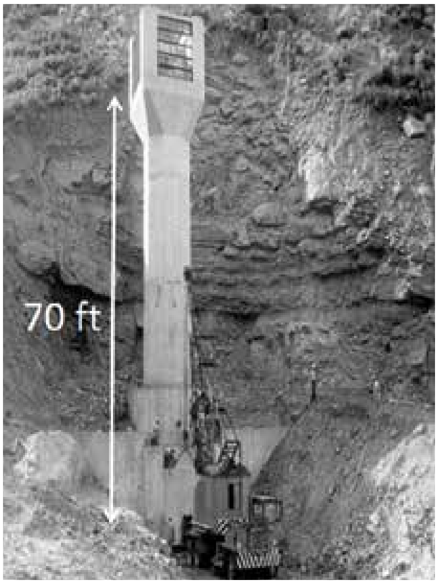
Inconsistent interpretation of federal, state, and local permitting processes makes the application process complex and unpredictable. Factors include variations in how different U.S. Army Corps of Engineers (USACE) districts interpret existing permit frameworks and implement their regulatory programs, reflecting differences in regional conditions and in regulatory perspectives across states. The process is also hampered by a lack of consistent and adequate training and knowledge about sediment transport processes and about interactions between sediment movement, river morphology, and ecosystem response among staff at regulatory and resource agencies (e.g., the Environmental Protection Agency, U.S. Fish and Wildlife Service, NOAA), dam operators, nongovernmental organizations, and permittees.

In addition, examples of poorly designed and timed sediment discharges from reservoirs have caused legitimate concerns about negative effects on downstream ecosystems [*Espa et al.*, 2016]. Taken together, these issues highlight why current regulatory tools are not favorable for sustainable management of reservoir sediments. However, they also reveal opportunities for modernizing those tools and ameliorating reservoir sediment management.

Achieving Sustainable Reservoirs for the Future

Broadly speaking, the following three key challenges characterize the current regulatory framework for authorizing sediment discharges from reservoirs:

- The definition of sediment as a pollutant and as fill under Section 404 of the CWA
- Traditional engineering practices that do not account for current knowledge of geomorphic and ecological processes, as well as a



The 21-meter outlet structure at Paonia Reservoir is shown under construction in 1961. Credit: U.S. Bureau of Reclamation

lack of training on and common understanding of these processes

- Regulations that are simultaneously inflexible (e.g., de minimis) and inconsistent

We identify four interrelated recommendations to address these challenges.

Recommendation 1

Broaden the Interpretation of De Minimis Sediment Release. Individual permits for sediment discharges are not needed when the amount of sediment released is below a de minimis standard. De minimis is a concept established by USACE as a sediment release that approximates the natural load of sediment entering the reservoir. However, it is difficult to flush stored sediment if the load released must be similar in magnitude, composition, and seasonal pattern to that entering a reservoir.

Releases of accumulated sediment loads could be authorized if de minimis standards were based on relevant geomorphic or ecologic criteria and had the goal of preventing degradation of aquatic resources (see recommendation 4). Such a framework would require robust and quantitative understanding of local hydrological, geological, and ecological processes. This type of framework would benefit from establishing a community of practice (COP), and implementing it would require training of permitting staff and practitioners on new processes and tools (recommendation 2).

Recommendation 2

Establish Reservoir Sediment Management Communities of Practice. USACE has previously established COPs to encourage collaboration and efficiency of applications and knowledge transfers across different technical fields (e.g., the Levee Safety COP, which engages a wide range of practitioners and regulators in collecting data, database building, and assessment of tools and policies for increasing levee safety). We recommend establishing a COP for reservoir sediment management. Key efforts of this COP could include the following:

- Developing a reference database of existing reservoir sediment management permits under Sections 401 and 404 of the CWA (Section 401 deals with permitting water discharge events with respect to their effects on water quality).
- Developing a screening tool with specific metrics (e.g., sediment types, management strategy, accumulation and expected release rates). The screening tool would help practitioners and regulators to identify high-risk sites where more careful design and monitoring are needed and to manage impacts to downstream infrastructure and ecosystems. It would also inform the permitting process.
- Convening and supporting experts to review best practices for defining de minimis criteria (recommendation 1) and for designing sediment discharge operations to minimize operational and economic burdens while maximizing ecological benefits.
- Convening permitting staff, resource agencies, and practitioners for instruction and training on the intersections of sediment and ecological processes and on evaluating, mitigating, and communicating potential risks of increasing sediment releases to downstream reaches.

Recommendation 3

Establish Regional General Permits for Regular Downstream Sediment Releases. We recommend that USACE districts issue regional general permits (RGPs) for sediment management that are specific to geographic areas. Current RGPs authorize desilting flood control channels, maintenance dredging of water bodies, beneficial reuse of dredged sediment, ecological restoration activities, and emergency activities. New RGPs that allow regular managed releases of sediment from reservoirs should be established. This update would streamline permitting for projects that cause minimal and predictable adverse environmental impacts to aquatic resources, allow for regular renewals, and motivate application of best practices for sediment management.

For example, in watersheds that are highly erodible and that naturally experience regular, event-driven sediment pulses, an RGP could allow for multiple sediment discharge events spaced out over repeated episodes. Such multiple smaller releases would generally produce smaller downstream impacts than a single, large sediment release. Ultimately, an RGP will be most effective if it is based on a framework that recognizes local characteristics of catchments, reservoirs, and downstream areas.

Current regulatory tools are not favorable for sustainable management of reservoir sediments, but there are opportunities for modernizing those tools.

Recommendation 4

Adapt a Flexible and Collaborative Approach Based on Local Conditions. Because sediment management at reservoirs is uncommon in the United States, the permitting process for such projects is particularly convoluted and protracted. A collaborative approach to permitting thus would be beneficial [*Ulibarri et al.*, 2017]. Early and frequent communication among regulators, stakeholders, and permittees could facilitate common understanding of reservoir dynamics on the timelines of geomorphic and ecological processes as well as risk identification.

A collaborative approach would streamline permitting and reduce delays in obtaining CWA Section 401 and 404 permits. It would also assist in identifying points of flexibility in the design and permitting processes that best serve the project and the environment. Recent dam removals in the United States have demonstrated regulators' flexibility to permit activities that allow moderate short-term degradation while maintaining and protecting existing uses of a waterway (e.g., for aquatic habitat, drinking water supply, channel maintenance, recreation). For example, dam removals in the Pacific Northwest have been timed to avoid negative effects on

salmon eggs and to take advantage of seasonal weather conditions.

Dam removals are very similar to operations aimed at maintaining reservoir capacity in the type and duration of sediment releases; both generate sediment pulses that peak at the end of drawdown and during subsequent storm events, for example. These pulses ultimately benefit ecosystems by reestablishing natural sediment flows and improving environmental conditions [*Bellmore et al.*, 2019].

Acknowledgment of long-term benefits of sediment releases by regulators can boost flexibility in setting timetables for dam managers to achieve regulatory compliance and for establishing water quality criteria aligned with the principle of antidegradation of aquatic resources (i.e., weighing the pros and cons of a proposed activity that could degrade water quality). For example, the CWA Section 401 permit allowing for removal of the J. C. Boyle Dam on Oregon's portion of the Klamath River—currently scheduled for initiation in 2023—established a compliance period (the deadline by which standards must be met) of 24 months. This provision will allow dam removal operations to avoid liability for water quality violations during sediment releases immediately following the removal.

Another accommodation that recognizes real-world conditions involves transitioning from using water quality criteria simply based on changes from background concentrations to using biologically based criteria, such as suspended sediment concentrations that damage fish gills or lead to lethally low dissolved oxygen. Such criteria balance the short-term degradation of water quality that aquatic organisms and resources can tolerate before suffering permanent degradation with the long-term benefits of restored sediment continuity.

Blending knowledge of local ecosystems, weather, geomorphic factors, and trapped sediment allows dam and natural resource managers to design sediment removal programs that minimize negative impacts to the environment and downstream users.

A Shift in Strategy

Many of the tools that U.S. regulators and managers need for implementing improvements in sediment management already exist. Applying advanced knowledge gained from physical, biological, and environmental sciences will help improve the sustainability of the nation's constructed reservoirs and its ecosystems. And implementing policy recommendations based on science and practical experience would put the United States more in line with approaches currently being used in Europe and Asia. The shift in regulation strategy proposed here would provide a means to manage sediment that is better able to maintain reservoir integrity in the future under demands associated with climate change, aging infrastructure, and public safety.

Fundamentally, achieving sustainable reservoir management requires acknowledging that sediment is not a pollutant but is, instead, like water, often a beneficial resource that must be wisely managed. The failure to acknowledge and account for this truth has led to devastating consequences for people and ecosystems in the past, and such consequences will occur more often and become more severe in the future unless we change our approach.

Even when reservoir outlets are built above their respective sediment storage pools, like this one at Paonia Reservoir, they can become buried in sediments over time. Credit: U.S. Bureau of Reclamation

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Microplastics' Hidden Contribution to Snow Melting

Black carbon particles, produced by combustion of gasoline, diesel fuel, coal, and other organics, have been found to be the second-largest driver of climate warming, after carbon dioxide (CO_2), since the Industrial Revolution [*Myhre et al.*, 2013]. Much of black carbon's role in this warming results from the fact that it contributes to the melting of snow and ice and thus to darkening of Earth's surface, reducing the amount of sunlight the planet reflects and increasing the amount it absorbs.

These processes have been thoroughly studied, yet measurements made in the past of black carbon particles in snow and determinations of their effects on melting may be inaccurate. To date, most studies have overlooked a major and potentially complicating factor: microplastics. Here we address the possible implications of this issue and offer recommendations to promote more accurate assessments of the effects of both black carbon and microplastics on snow and climate.

Massive Amounts of Uncounted Microplastics

Microplastics are tiny plastic particles, fibers, or fragments smaller than 5 millimeters across—and they are everywhere. They have been implicated in a range of environmental effects, including bioaccumulation in fish and in human blood and feces. These particles have reached Earth's least populated areas, including the High Alps, the Arctic [*Bergmann et al.*, 2019], and even Antarctica [*Kelly et al.*, 2020]—in fact, everywhere scientists look, they find microplastic particles. Microplastics and black carbon have been depositing together in snow since the 1950s, when plastics and petroleum products came into widespread use.

Today the mass of microplastics in the environment is very likely more than that of black carbon. *Dubaish and Liebezeit* [2013] found 5 times more microplastics than visible black carbon particles in a microscope slide count of particles in water samples from Jade Bay along the northwestern coast of Germany. This is the only study to date that has reported simultaneous measurements of microplastics and black carbon particles, and it did not address the coexistence of microplastics and black carbon in snow.

Wind can loft microplastics particles above the ground and carry them onto snow surfaces [*Evangeliou et al.*, 2020], where, calculations have shown, they can remain for hundreds of years before they completely decompose. Microplastics are now believed to have spread to every human-reached corner of Earth [*Brahney et al.*, 2020; *Pabortsava and Lampitt*, 2020]. So when field researchers sample snow for black carbon laboratory measurements, they inevitably bottle or bag microplastics together with black carbon—and both types of particles may be counted together during measurement and analysis.

Very few studies of black carbon in snow have tried to separate out microplastics before making instrumental measurements. This long-term neglect of microplastics in snow zin past studies may have resulted in overestimations of the black carbon content in snow and of its effects on glaciers, snow cover, ice sheets, and climate. Unfortunately, climate change assessments, so far, also have not included the role of microplastics in snow.

It's All the Same to the Instruments…

The risk in not separating microplastics from black carbon before conducting lab measurements is that the effects of the two types of particles could be confounded, impairing our understanding of the true effects of each on snow and climate. Why is this? Microplastics and black carbon may be indistinguishable in the results of thermal-optical and pyrolysis-based laboratory tests (Figure 1).

The most-used plastics include polyethylene, polypropylene, polystyrene, and polyvinyl chloride, along with smaller amounts of other plastics. Combustion experiments demonstrate that plastics ignite and burn in oxygen at temperatures between 500°C and 1,000°C. Because the main elements composing plastics are carbon (roughly 85%), hydrogen (roughly 14%), and oxygen (less than 1%), the gases released when these plastics are completely combusted are CO_2 and H_2O [*Zevenhoven et al.*, 1997].

Black carbon particles, which consist mostly of carbon, oxidize in air between 500°C and 700°C and form CO_2 if combustion goes to completion [*Andreae and Gelencsér*, 2006]. The overlap in the oxidation temperature ranges of black carbon and microplastics implies that pyrolysis-related techniques may produce results in which the black carbon signal is contaminated by microplastics in a sample.

Likewise, optical absorption techniques such as aethalometry (light absorption by aerosol particles collected on filters) and laser-induced incandescence (light absorption by nebulized samples) may also combine signals from microplastics and black carbon. Many types of microplastics are brightly colored or black and absorb light in the visible and near-infrared wavelengths [Alexander et al., 2008], just as black carbon particles do.

Until recently, light-absorbing constituents in snow samples measured using the above methods were implicitly presumed to be black carbon, organic carbon, or dust, and the probable coexistence of microplastics was overlooked.

…But the Environment Knows the Difference

Almost all "clear" plastics are nearly transparent in the UV–visible wavelengths [*Ishaq*, 2019]. These plastics, deposited on snow, do not perturb the solar radiation balance. However, most plastic products are dyed or painted, which causes them to absorb light. For example, red plastics absorb green light, blue plastics absorb yellow light, and black plastics absorb a wide range of wavelengths. In addition, as plastics weather and break down, partly because of sunlight absorption, the resulting microplastics can turn from transparent to translucent. Tearing, scratching, and aging processes such as these cause microplastics particles to absorb more light.

In light of potential interference from microplastics, previous measurements of black carbon in snow may need to be reviewed and the radiative effects of black carbon and microplastics in snow co-assessed.

Increased light absorption by microplastics may contaminate assessments of black carbon's impacts on snow albedo (the fraction of sunlight that snow reflects), and

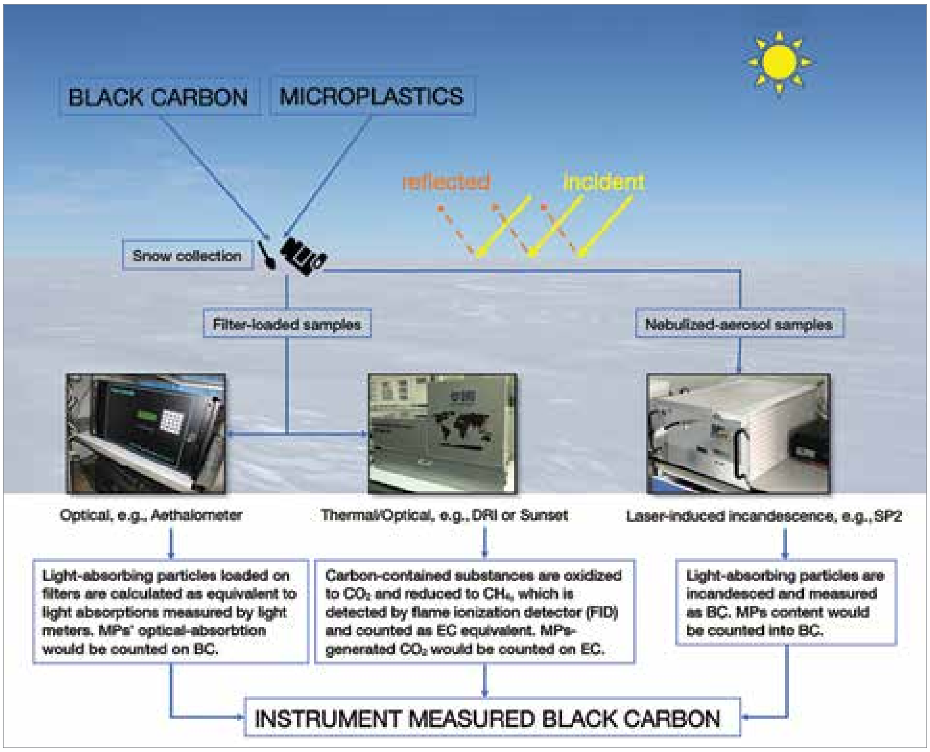

Fig. 1. Three commonly used laboratory analysis methods may combine signals from microplastics and black carbon particles, but the two types of particles might affect snow albedo differently. DRI and Sunset are instrument company names; EC is elemental carbon; SP2 is single particle soot photometer.

thus on its contribution to calculations of radiative balance, in two ways. One is that microplastics may be responsible for part of the reduced snow albedo that current lab tests ascribe entirely to black carbon. The other is that measured amounts of equivalent black carbon (a value determined using a mass absorption coefficient that may include substances other than black carbon) can overestimate the amount of actual black carbon if the equivalent black carbon amounts include significant contributions from microplastics.

Although natural environmental temperatures never get high enough to convert black carbon and microplastics particles to CO_2 (except perhaps near active wildfires or volcanoes), laboratory analyses using pyrolysis methods are another matter. In such analyses, both black carbon and microplastics are oxidized to CO_2, and measurements reflect contributions from both species. Calculations of black carbon thermally converted to CO_2 in instruments may thus be inflated by unrecognized contributions from microplastics in current instrument analyses.

A Work-Around to Measure Black Carbon and Microplastics in Snow

Considering the potentially significant complications that microplastics pose for our understanding of black carbon's effects on snow melting and climate, it is clear that research is urgently needed to determine the extent—or lack thereof—to which scientists can distinguish these particles using different analytical methods. It is also very important to quantify the co-occurrence of microplastics and black carbon in snow samples collected for lab measurements.

So far, no protocols have been applied to separate these particles prior to instrumental analysis of black carbon in snow or ice. We thus suggest the following simple preprocessing protocol to separate microplastics and black carbon in snow samples before testing:

- Use glass bottles instead of plastic ones when collecting field samples to avoid plastic contamination from sampling bottles.
- Filter melted snow samples through filters with micrometer-sized pores to remove relatively large microplastics particles.
- Centrifuge samples to separate smaller microplastics particles. (The density of black carbon particles is greater than 1.8 grams per cubic centimeter, whereas most plastics have a density of less than 1.4 grams per cubic centimeter.)

In light of potential interference from microplastics, we also suggest that previous measurements of black carbon in snow may need to be reviewed and the radiative effects of black carbon and microplastics in snow co-assessed. Such a reassessment could assist in identifying the true sources of particle pollution and melting in snow and increase the effectiveness of remediation efforts.

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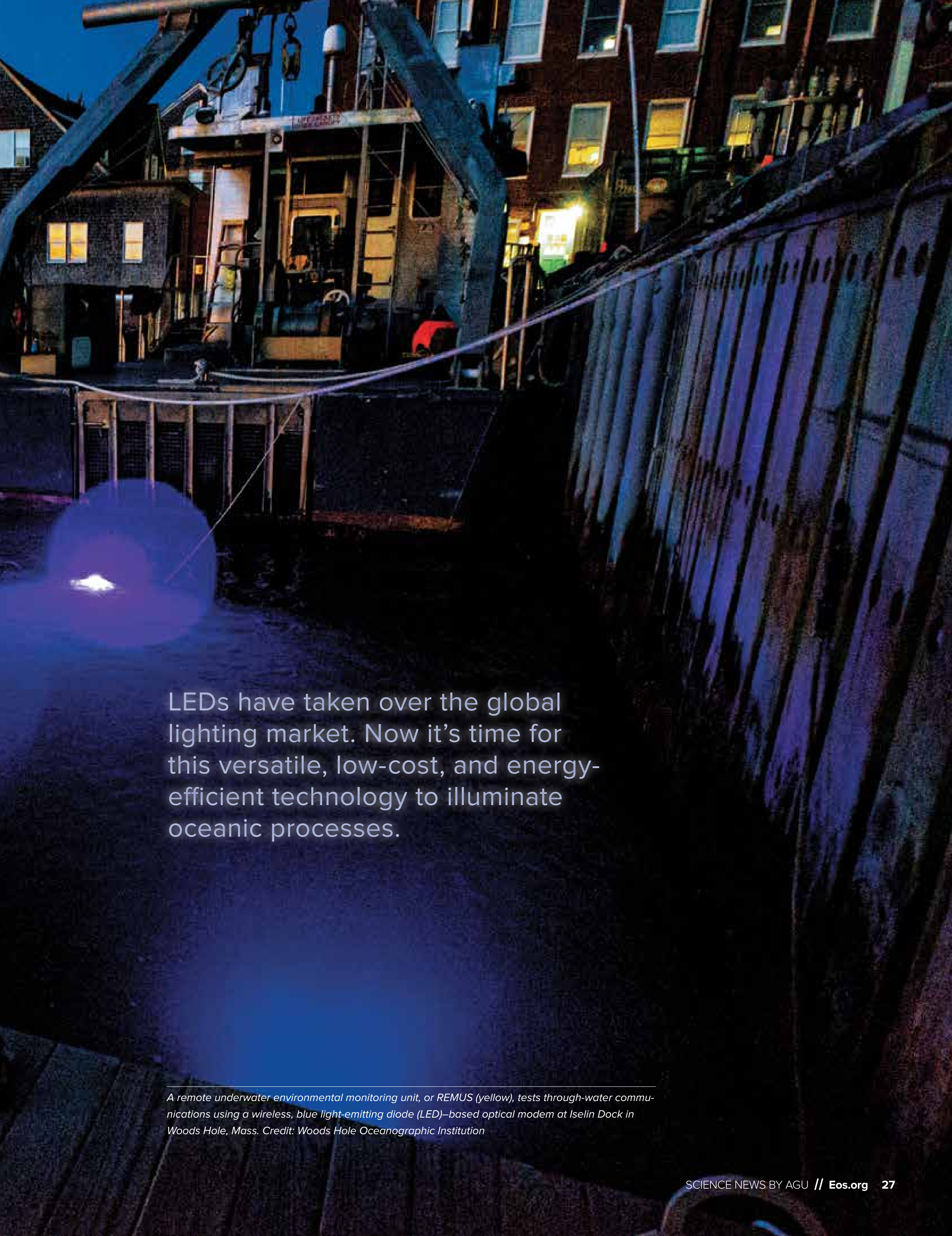
A BRIGHT, LED-LIT FUTURE FOR THE OCEAN SCIENCES

By Collin P. Ward



LEDs have taken over the global lighting market. Now it's time for this versatile, low-cost, and energy-efficient technology to illuminate oceanic processes.

A remote underwater environmental monitoring unit, or REMUS (yellow), tests through-water communications using a wireless, blue light-emitting diode (LED)–based optical modem at Iselin Dock in Woods Hole, Mass. Credit: Woods Hole Oceanographic Institution

Cutting the cord at home—replacing traditional cable television service with alternatives like streaming video—is an increasingly common trend these days. In oceanography, scientists are seeing their own version of this trend, one that might more accurately be called "cutting the tether." Both trends have been matched—and aided—by the rapid growth of light-emitting diode (LED) technology and applications.

Recently, there has been a push in the oceanographic community to replace hardwired, fiber-optic communication tethers connected to instruments with wireless, through-water communications. Think Wi-Fi for the ocean. For example, in 2019, untethered, wireless communications allowed then Seychelles president Danny Faure to address his constituents and raise awareness about ocean health from a submersible vehicle 124 meters below the sea surface, an event that was livestreamed to thousands around the world. The core technology that made this livestream possible comprised high-powered, blue LEDs that package and rapidly transmit data through the water [*Farr et al.*, 2010].

LEDs Have Transformed How We Light Our Homes...

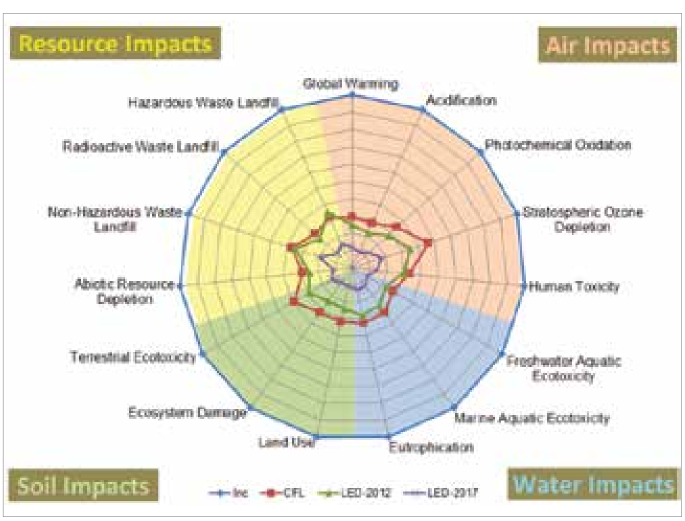
The foundational technology of LEDs has been around for more than a century, but only in the past decade or so have LEDs become transformative to society.

> **The foundational technology of light-emitting diodes (LEDs) has been around for more than a century, but only in the past decade or so have LEDs become transformative to society.**

In 2010, LEDs accounted for 1% of the global lighting market; by 2020, this share had risen to 55%. This rapid growth has profoundly reshaped the industry, even contributing to the decision by General Electric, long known as the leading innovator in lighting, to sell its lighting division in 2020. At some point this decade, the entire global lighting market is expected to shift to LEDs, with the LED lighting market rising from roughly $60 billion in 2021 to an estimated $135 billion in 2028.

The transition from incandescent bulbs to LEDs has been driven by both policy changes and consumer demand. In the United States, for example, the Energy Independence and Security Act passed in 2007 mandated that many household lightbulbs become 25% more efficient than incandescent bulbs. Similar polices have been adopted by the European Union and China.

These policy changes left consumers with two options: compact fluorescent lamps (CFLs) or LEDs. LEDs are more than 40% more energy efficient and last 3–7 times longer than CFLs, and as LED bulb prices have dropped, consumers have increasingly opted for them.



Shown here are the relative magnitudes of impacts of different lighting sources over their life cycles on natural resources, air, soil, and water. The impacts of compact fluorescent (red) and LED (green and purple) bulbs are substantially less than those of incandescent bulbs (blue). Credit: U.S. Department of Energy

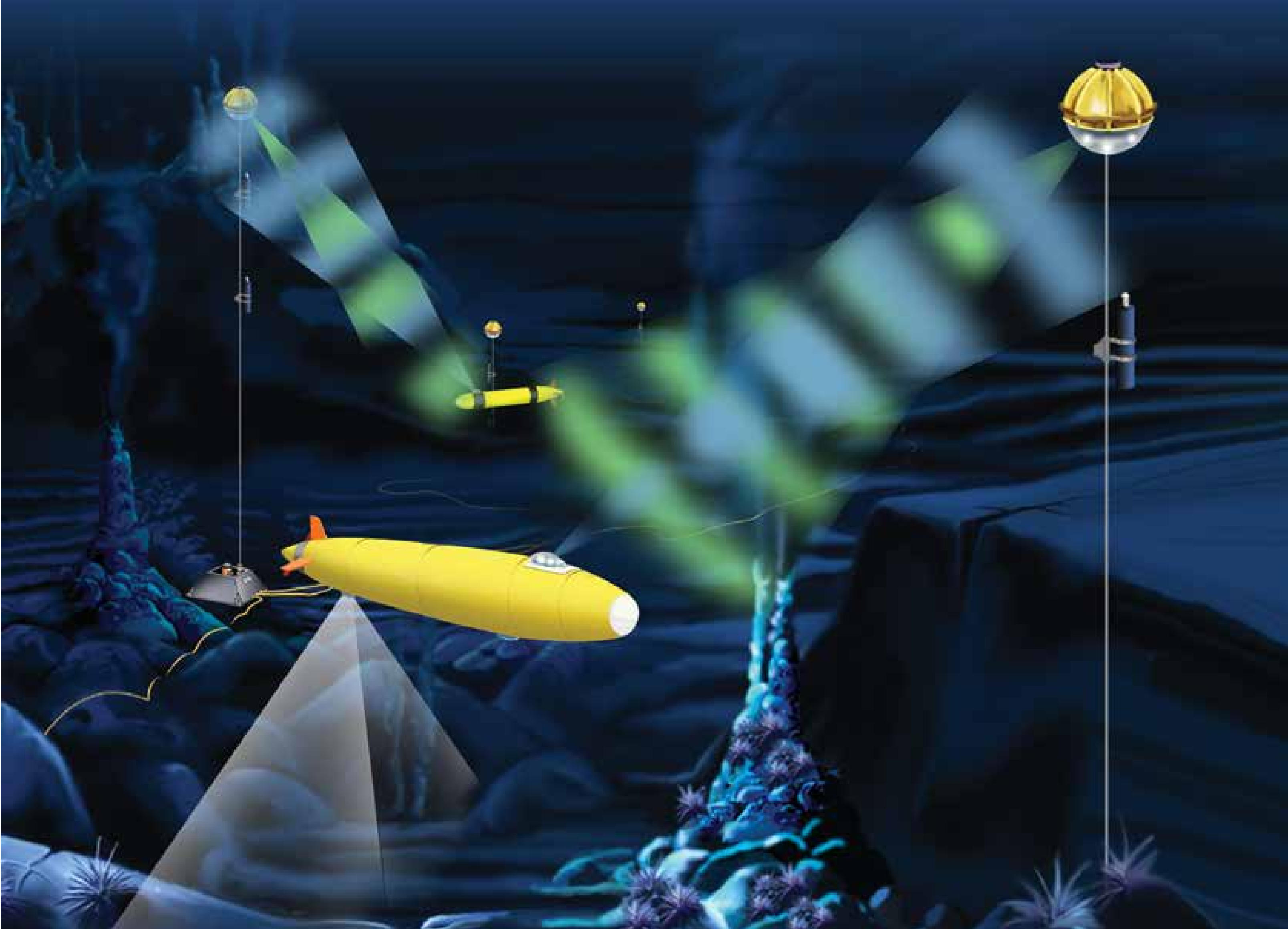
Although the choice for consumers has been relatively easy to make, many people do not fully appreciate the positive environmental impacts of adopting LED technology. In 2017, information provider IHS Markit estimated that the adoption of LED lighting reduced global carbon dioxide emissions that year by more than half a billion tons, or 1.5%. Life cycle assessments also indicate that compared with using incandescent or CFL bulbs, LED technology reduces hazardous waste production and risks to ecosystem and human health and better preserves air, soil, and water quality.

...And Now They Are Transforming How We Study the Ocean

The future of studying the ocean lies in the development of low-cost vehicles, sensors, and instruments. These tools will enable continuous monitoring of ocean processes and allow a broader contingent of the global population to participate in ocean research and sustainability efforts. LEDs, which are useful not only for underwater lighting but also for transmitting data through water, are primed to play an important role in this future vision.

The oceanographic research community is currently developing fleets of autonomous underwater vehicles (AUVs) to collect physical, acoustic, chemical, and biological data that help us understand how the ocean works and how it will respond to human-induced pressures from climate change and pollution. For example, these fleets collect data that characterize (1) the changing strengths of ocean currents like the Gulf Stream; (2) the distribution and sustainability of commercially important fisheries; (3) the locations and movements of endangered marine mammals in proximity to shipping vessels and fishing gear; (4) changes in water quality parameters like pH, temperature, nutrient loads, and oxygen levels; and (5) greenhouse gas storage. These fleets also monitor the integrity of and ecosystem impacts from ocean infrastructure like installations for offshore oil exploration, wind energy production, and aquaculture.

In theory, these fleets will be able to take measurements across more expansive spatial and temporal scales than are currently possible while also minimizing the use of expensive and energy-intensive crewed research vessels. But for these AUV fleets to be more than just groups of individual vehi-



Autonomous underwater vehicles (AUVs) communicate and work together to survey a hydrothermal vent at the bottom of the ocean in this illustration. LED lights aboard the AUVs transmit data collected through the water to receivers secured to cabled moorings. Fiber-optic cables then deliver the data from the moorings to scientists on shore, allowing them to inspect the data and, if needed, adjust their research plan in near-real time. Credit: Woods Hole Oceanographic Institution

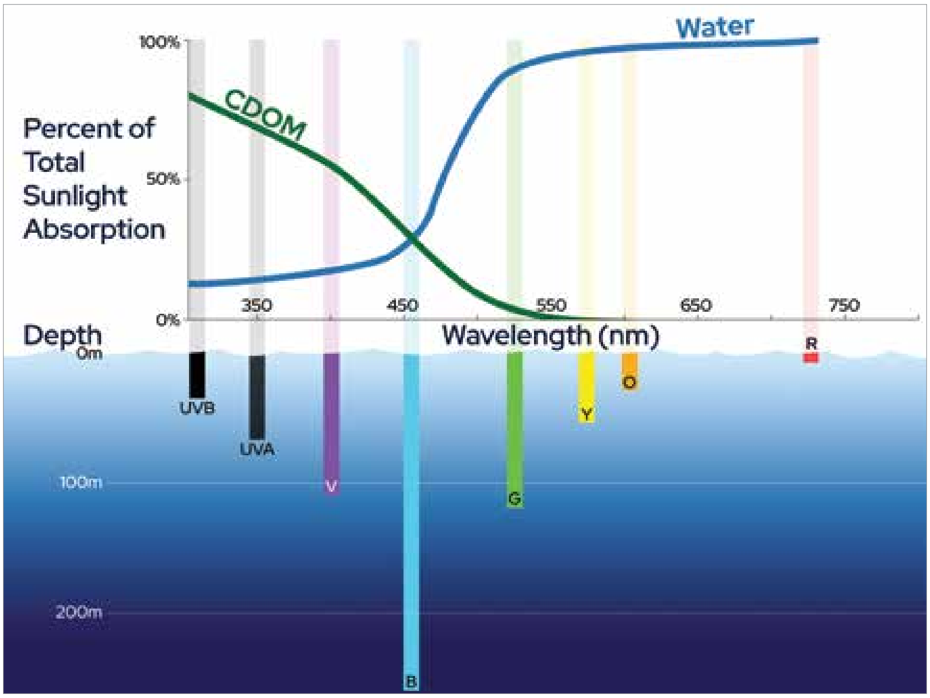
cles operating in proximity, they need to communicate and coordinate their activities. This is where advanced LED technology comes in.

An estimated 436 submarine fiber-optic cables, totaling 1.3 million kilometers in length (enough for 32 trips around Earth's equator), are currently in service, making up a complex global web of rapid-transmission communications conduits. It is this web that allows us to call friends and family nearly anywhere around the world with the touch of a button. Data are communicated through these specialty glass-lined cables in the form of high-powered light, often emitted by LEDs, that bounces from side to side in a process known as total internal reflection. Without these fiber-optic cables (i.e., if the cord, or tether, were cut), light-borne data could not travel nearly as far because the light emissions attenuate quickly.

The choice of light color makes a difference, however. In the ocean, the main attenuators of light are chromophoric dissolved organic matter (CDOM) and water itself. CDOM readily absorbs ultraviolet (UV) light, whereas water readily absorbs green and red light. Because blue light largely escapes absorption by CDOM and water, it travels hundreds of meters into the ocean, much deeper than UV, green, and red light. This is why the ocean is blue and why wireless underwater optical communication systems use high-powered blue LEDs to transmit data.

Wireless underwater LED technology is, in fact, already largely proven and in use. For example, at a seafloor borehole observatory, LED-based optical modems rapidly transmit data from in situ sensors to AUVs or remotely operated vehicles more than 100 meters away—just as similar modems did during President Faure's livestream from Seychelles. Moreover, as seabed pipelines that deliver oil and gas from thousands of active offshore rigs to refineries on land are built and maintained, LED-based optical modems help rapidly transfer data to engineers. These data allow the engineers to monitor and react in near-real time to conditions at the seafloor, improving the accuracy and speed with which the pipelines can be laid and optimizing monitoring of pipeline health to avoid, or at least minimize, damages and environmental harm from undersea pipeline ruptures.

LEDs can also help ensure that high-quality data are collected. All sensors in the ocean—whether optical, chemical, electrical, or acoustic—are prone to biofouling or other interferences from living organisms like algal slime and barnacles that grow on sensor surfaces. Traditional approaches to



The relative importance of chromophoric dissolved organic matter (CDOM) and water to total light attenuation in the ocean is depicted here. (top) CDOM is the main attenuator of UVB, UVA, and violet light, whereas water is the main attenuator of green, yellow, orange, and red light. (bottom) Blue light penetrates deepest into the ocean because it escapes absorption by CDOM and water.

minimizing biofouling involve mechanical means like wipers and shutters or chemical means like biocides. These approaches, however, leave a lot to be desired, particularly in the application of biocides that can cause collateral harm to more than just the intended organisms.

In turn, oceanographic researchers have recently been pushing for chemical-free antifouling alternatives. Given their simplicity, low costs, and power requirements, UV LEDs, particularly those that emit UVC, appear to be the wave of the future [*Delgado et al.*, 2021], and preliminary results on their effectiveness are promising. UVC treatment has been shown to minimize biofouling of ocean sensors, improving the quality of pH, conductivity, and turbidity data collected [*Bueley et al.*, 2014; *Armstrong and Snazelle*, 2017], and to allow longer deployments at sea.

Adding to the Photochemical Toolbox

From UV LEDs used for disinfection to visible light LEDs used for communications, the wavelengths generated by LEDs span the entire range of natural sunlight that reaches the sea surface. This fact opens the door for scientists to use LEDs to study how sunlight alters the cycling of major and minor elements and the fate of pollutants in the ocean, processes that influence marine ecosystems and the overall Earth system in countless ways.

Aquatic photochemistry as a discipline has grown immensely over the past half century, yet in that time our understanding of how the rates of light-driven reactions depend on sunlight wavelength has not changed much. This knowledge gap matters because reaction rates of photochemical processes vary considerably from day to day, even hour to hour, and at different depths in the ocean for several reasons. First, the energy of light photons decreases with increasing light wavelength; for example, UV light is more energetic than blue light, which in turn is more energetic than red light. This variation is why sunscreen contains mineral additives that specifically block powerful, and biologically hazardous, UV light. It's also why red pigments in street signs and artistic masterpieces fade quicker than blue pigments: More powerful blue light is absorbed by and destroys red pigments, causing visible fading, whereas absorption of less powerful red light allows blue pigments to last longer. Second, although visible light is weaker than UV light, about 10 times more visible light reaches Earth's surface than UV light [*Apell and McNeill*, 2019]. Third, different light wavelengths penetrate into the ocean to different extents, with blue light penetrating the deepest.

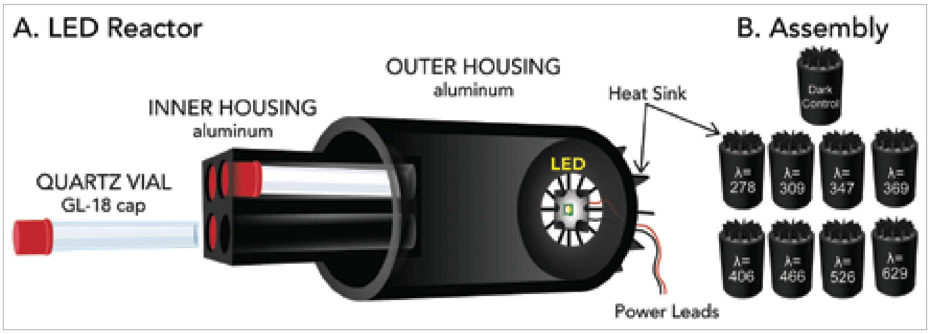
*Conductivity data collected using a conductivity probe deployed at sea for several months and treated with UVC light (left) matched very closely with true values, whereas data collected from a biofouled probe not treated with UVC (right) drifted away from the true values within a week [*Bueley et al., *2014]. Credit: Ocean Networks Canada and AML Oceanographic*

Our limited understanding of the wavelength dependence of aquatic photochemical reactions is driven largely by cost and technological limitations. Determining wavelength dependence requires specialized equipment like high-powered lasers, solar simulators, and monochromators, which help isolate different wavelengths of the solar spectrum. This equipment is costly and energy intensive and lacks portability, often requiring researchers to stabilize or preserve their field samples for experimentation back in laboratories on land. Moreover, these approaches have low sample throughput—only one or two samples can be analyzed per day, which considerably raises labor costs.

LEDs present an exciting opportunity to overcome many of these limitations without sacrificing data quality [*Ward et al.*, 2021], allowing a wider contingent of researchers to study rates of sunlight-driven processes over spatial and temporal scales that were previously inaccessible. Widespread adoption and application of this technology could thus allow the incorporation of photochemical processes into Earth system models and afford more accurate depictions of how major and minor elements and pollutants cycle in the upper ocean.

More People in More Places

The disruptive potential of LED technology is so broad that it is poised to play key roles in making progress toward several of the United Nations (U.N.) Sustainable Development Goals. These goals include eliminating pov-



The LED-based reactor assembly illustrated here was designed to determine the wavelength (λ) dependence of light-driven reactions in surface waters that affect, for example, cycling of major and minor elements and the fate of pollutants. Wavebands range from UVB (278 nanometers) to red light (629 nanometers). A discussion of the pros and cons of this assembly compared with other technologies (related to, e.g., costs, sample throughput, portability, and data quality), as well as a step-by-step plan to build and validate an assembly, is given by Ward et al.. *[2021]. Credit: Reprinted with permission from* Ward et al. *[2021], ©2021 American Chemical Society*

erty; ensuring good health and well-being for everyone; ensuring clean water supplies and adequate sanitation; fostering resilient and inclusive industry, innovation, and infrastructure; and conserving and sustainably using the oceans, seas, and marine resources.

For example, just as UVC LEDs are currently used to disinfect indoor air to combat the spread of the COVID-19-causing SARS-CoV-2 virus and other pathogens, UVC LEDs offer a low-cost and effective means to disinfect and destroy viruses and micropollutants in drinking water [*Chen et al.*, 2017]. Moreover, visible light LEDs are a foundational technology in vertical farming, a relatively new industry that grows crops in stacked layers under controlled conditions. A key aim of vertical farming is to alleviate negative ecosystem impacts of traditional farming operations, such as reduced carbon sequestration in soils, depleted and impaired freshwater resources, and damages caused by pesticide and herbicide applications [*Benke and Tomkins*, 2017].

In particular, the effect of LEDs on the goal of sustainably using the oceans is becoming increasingly clear. Ocean science is global by nature, but in practice, participation is limited largely to institutions, scientists, and students in wealthy nations while being cost prohibitive in lower-income nations and for many people in ocean-dependent communities. In response to the U.N.'s call for a Decade of Ocean Science for Sustainable Development, which began in 2021, many scientists have argued for improving sustainability and equity in the ocean sciences community [*Pendleton et al.*, 2020; *Singh et al.*, 2021; *Valauri-Orton et al.*, 2021; *Wang,* 2021]. One common recommendation in these arguments is to invest in the development of low-cost sensors and technologies to lower barriers and encourage broader participation.

Just as low-cost LED-based sensors empower air quality monitoring in developing nations that disproportionately experience the health burden of poor air quality, it is likely that LEDs will contribute substantially to the development of low-cost sensors to monitor ocean health. Such an evolution could advance equity in the ocean sciences, allowing more people in more places to participate. It could also advance sustainability by allowing us to observe and monitor more of the ocean more often, offering a wealth of information about marine conditions and health with which to make informed decisions about how we treat it.

It is likely that LEDs will contribute substantially to the development of low-cost sensors to monitor ocean health, an evolution that could advance equity in the ocean sciences.

Acknowledgments

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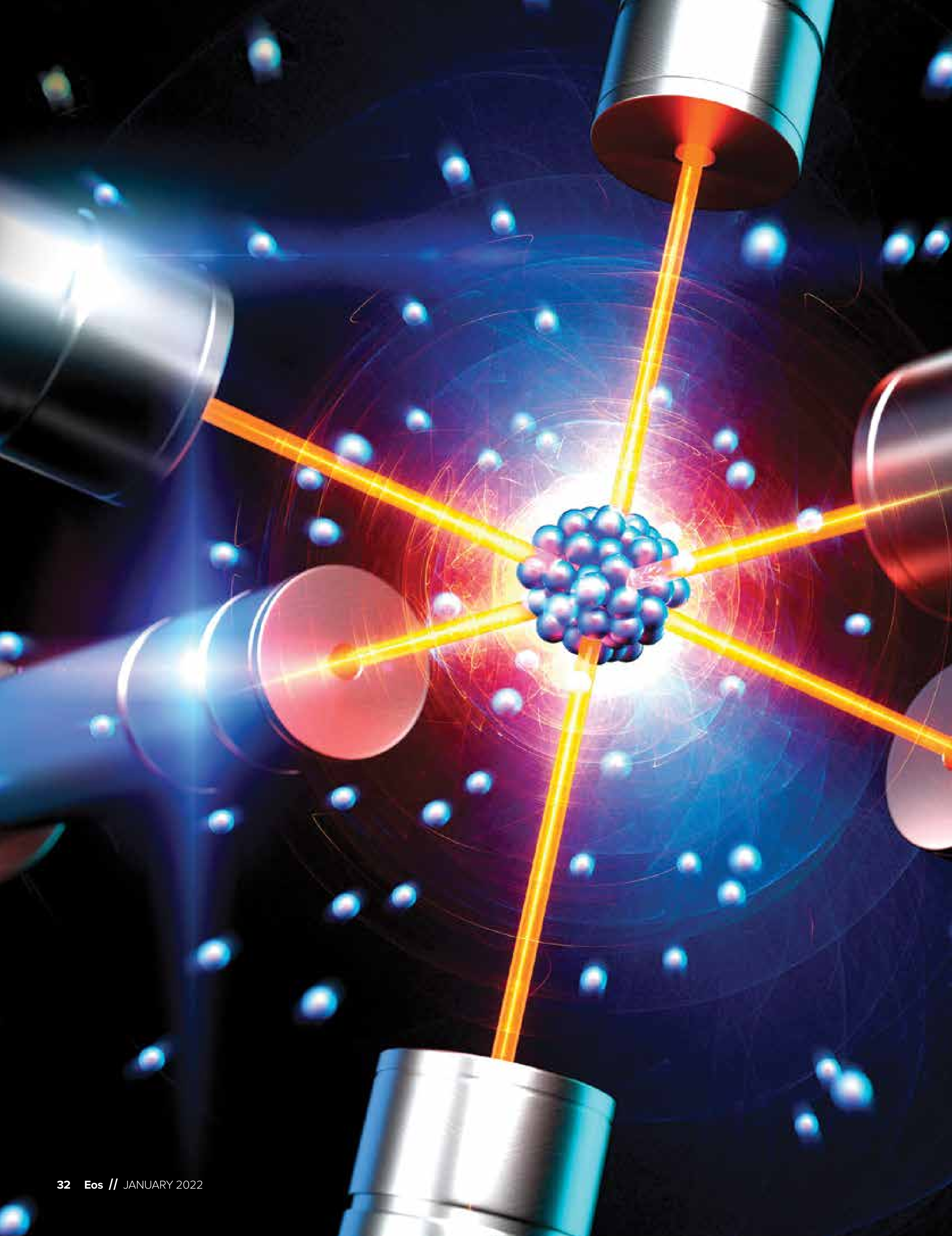

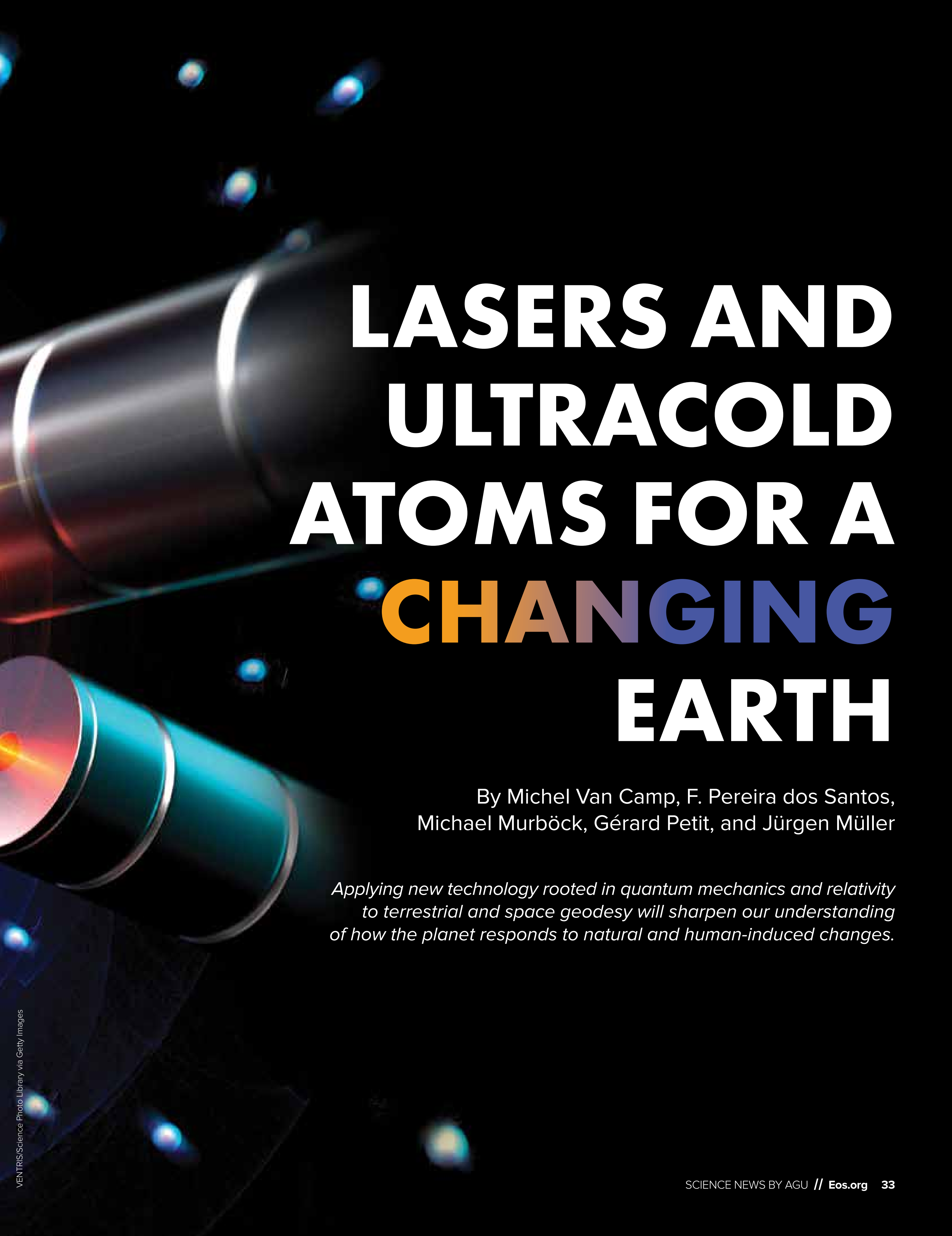

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LASERS AND ULTRACOLD ATOMS FOR A CHANGING EARTH

By Michel Van Camp, F. Pereira dos Santos, Michael Murböck, Gérard Petit, and Jürgen Müller

Applying new technology rooted in quantum mechanics and relativity to terrestrial and space geodesy will sharpen our understanding of how the planet responds to natural and human-induced changes.

Quantum mechanics rules the atomic world, challenging our intuitions based on Newton's classical mechanics. And yet atoms share at least one commonality with Newton's apple and with you and me: They experience gravity and fall in the same way.

Of course, observing free-falling atoms requires extremely sophisticated experimental devices, which became available only in the 1990s with the advent of laser cooling. Heat represents the extent to which atoms move, so cooling atoms eases their manipulation, allowing scientists to measure their free fall and to quantify and study the effects of gravity with extraordinary precision. Creating samples of ultracold atoms involves slowing the atoms using the momentum of photons in specialized laser beams.

Today novel developments in methods using ultracold atoms and laser technologies open enhanced prospects for applying quantum physics in both satellite and terrestrial geodesy—the science of measuring the shape, rotation, and gravity of Earth—and for improving measurement reference systems. Such methods have great potential for more accurately monitoring how the Earth system is responding to natural and human-induced forcing, from the planet's solid surface shifting in response to tectonic and magmatic movements to sea level rising in response to melting glaciers.

Taking Earth's Measure

Earth's shape is always changing, even if the changes are mostly imperceptible to us humans. In the subsurface, large convection currents and plate tectonics influence each other, shifting huge masses of rock around and causing earthquakes and volcanic eruptions. On the surface, the ocean, atmosphere, glaciers, rivers, and aquifers never rest either—nor do we as we excavate rock, extract groundwater and oil, and generally move mass around. All these movements subtly affect not only the planet's shape but also its rotation and its gravitational field.

Geodetic methods allow us to measure minute quantities that tell scientists a lot about Earth's size, shape, and makeup. As such, geodesy is essential to all branches of geophysics: tectonics, seismology, volcanology, oceanography, hydrology, glaciology, geomagnetism, climatology, meteorology, planetology, and even metrology, physics, and astronomy. Measuring these changes sheds light on many important Earth processes, such as mass loss from polar ice sheets, yet making these measurements accurately remains a challenging task (Figure 1).

Determining the elevation of an ice sheet's surface, to gauge whether it might have lost or gained mass, is often done using laser altimetry—that is, by observing the travel time of a laser beam emitted from a plane or a satellite and reflected off the ice surface back up to the observer. It's a powerful technique, but the laser does not necessarily distinguish between light, fresh snow and dense, old ice, introducing uncertainty into the measurement and into our understanding of the ice sheet's change.

Beyond this ambiguity, what happens if Earth's crust beneath the ice cap is deforming and influencing the elevation of the ice surface? Moreover, the altimeter's observation is relative: The elevation of the ice sheet surface is measured with respect to the position of the observing aircraft or satellite, which itself must be determined in comparison to a reference height datum (typically sea level). This feat requires measuring quantities that are exceedingly small compared with the size of Earth. If you drew a circle representing Earth on a standard piece of printer paper, even the 20-kilometer difference in height between Mount Everest's peak and the bottom of abyssal oceanic trenches—would be thinner than the thickness of your pencil line!

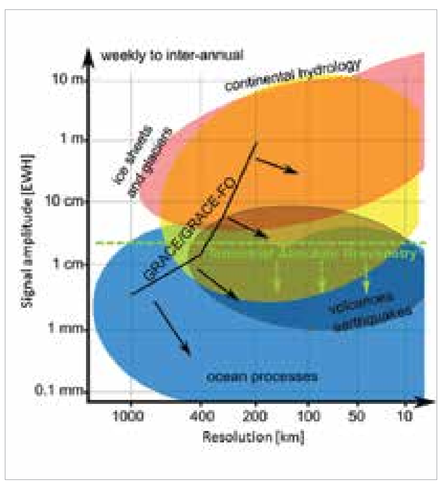


Fig. 1. The colored bubbles indicate the ranges of spatial resolution (in kilometers) and signal amplitude (in equivalent water height, EWH) characteristic of mass change processes related to continental hydrology (yellow), ice sheets and glaciers (pink), ocean processes (blue), and volcanoes and earthquakes (gray). The current measurement limits of laser interferometric ranging methods (e.g., aboard the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) missions; solid black line) and of terrestrial absolute gravimetry (dashed green line) are shown, along with the directions of improvement in these technologies (arrows) needed to cover more of the ranges of the processes. Credit: IfE/LUH

Meanwhile, measuring variation in Earth's rotation means determining its instantaneous orientation relative to fixed stars to within a fraction of a thousandth of an arc second—the amount Earth rotates in a few micro arc seconds. Assessing velocities and deformations of the tectonic plates requires determining positions at the millimeter scale. And detecting groundwater mass changes requires measuring the associated gravitational effect of a 1-centimeter-thick layer of water (i.e., equivalent water height, or EWH) spread over a 160,000-square-kilometer area. In other words, changes in Earth's rotation, deformations, and gravity must be measured with precisions that are 10 orders of magnitude shorter than the length of the day, smaller than Earth's diameter, and weaker than the gravity itself, respectively.

The Challenges of Attraction

Performing gravity measurements and analyses remains especially demanding. For land-based measurements, gravimeters are generally cumbersome, expensive, tricky to use and, in the case of the most precise superconducting instruments, require a high-wattage (1,500-watt) continuous power supply. In addition, most gravimeters, including superconducting instruments, offer only relative measurements—that is, they inform us about spatial and temporal variations in gravitational attraction, but they drift with time and do not provide the absolute value of gravitational acceleration (about 9.8 meters per second squared). Absolute gravimeters do, but these instruments are rare, expensive (costing roughly $500,000 apiece), and heavy. And as most are mechanical, wear and tear prevents their use for continuous measurements.

Moreover, terrestrial gravimeters are mostly sensitive to the mass distribution nearby, in a radius of a few hundred meters from the instrument. This sensitivity and scale allow observation of rapid and small-scale changes, such as from flash floods, in small watersheds or glaciers, and in volcanic systems, but they complicate data gathering over larger areas.

This absolute gravimeter developed by the SYRTE (Time and Space Reference Systems) department at the Paris Observatory uses ultracold-atom technology to make high-precision measurements of gravity. Credit: Sébastien Merlet, LNE-SYRTE

On the other hand, space-based gravimetry, realized in the Gravity Recovery and Climate Experiment mission and its follow-on mission, GRACE-FO, is blind to structures smaller than a few hundred kilometers. However, it offers unique information of homogeneous quality about mass anomalies over larger areas within Earth or at its surface. These missions can detect and monitor a mass change equivalent to a 1-centimeter EWH spread over a 400- × 400-kilometer area, with a temporal resolution of 10 days.

To monitor change from important Earth processes—from flooding and volcanism to glacier melting and groundwater movement—reliably and across scales, we need gravitational data with better spatiotemporal resolution and higher accuracy than are currently available (Figure 1). We also need highly stable and accurate reference systems to provide the fundamental backbone required to monitor sea level changes and tectonic and human-induced deformation. The needed improvements can be achieved only by using innovative quantum technologies.

The past few years have seen new efforts to develop such technologies for many uses. In 2018, for example, the European Commission began a long-term research and innovation initiative called Quantum Flagship. For geodetic applications, efforts are being coordinated and supported largely through the Novel Sensors and Quantum Technology for Geodesy (QuGe) program, a worldwide initiative organized under the umbrella of the International Association of Geodesy and launched in 2019. QuGe fosters synergies in technology development, space mission requirements, and geodetic and geophysical modeling by organizing workshops and conference sessions and by otherwise providing a platform where experts from different fields can collaborate.

A Quantum Upgrade for Gravity Sensing

QuGe emphasizes three pillars of development. The first focuses on investigations of ultracold-atom technologies for gravimetry on the ground and in space. Quantum gravimetry will benefit a comprehensive set of applications, from fast, localized gravity surveys and exploration to observing regional and global Earth system processes with high spatial and temporal resolution.

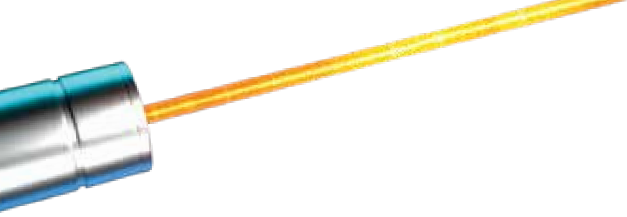
On Earth, the ideal instrument is an absolute, rather than relative, gravimeter capable of taking continuous measurements. This is not possible with a classical mechanical absolute gravimeter, in which a test mass is repeatedly dropped and lifted. In atomic instruments, there are no mobile parts or mechanical wear; instead, lasers control falling rubidium atoms. Recent achievements should enable production of such instruments on a larger scale, allowing scientists to establish dense networks of absolute gravimetric instruments to monitor, for example, aquifer and volcanic systems.

Today achieving dense coverage with gravimetric surveys, with measurements made at perhaps dozens of points, involves huge efforts, and sampling rates—with measurements taken typically once every month, year, or more—are still poor. Moreover, errors related to instrument calibration and drift remain problematic. Alternatively, a fixed instrument provides a measurement every second but at only a single location. The ability to continuously measure gravity at multiple locations, without the difficulties of drifting instruments, will allow much less ambiguous interpretations of gravity changes and related geophysical phenomena.

Measuring Earth's gravity field from space requires precisely monitoring the changing distance between paired orbiting satellites—as in the GRACE-FO mission—which accelerate and decelerate slightly as they are tugged more or less by the gravitational pull exerted by different masses on Earth. However, the satellites can also speed up and slow down because of forces other than changes in Earth's gravity field, including aerodynamic drag in the thin upper atmosphere. Currently, these other forces acting on the satellites are measured using electrostatic, suspended-mass accelerometers, which also tend to exhibit gradual, low-frequency drifts that hamper their accuracy.

The performance of these traditional accelerometers is thus challenged by quantum sensors, which have already demonstrated improved long-term stability and

Changes in Earth's rotation, deformations, and gravity must be measured with precisions that are 10 orders of magnitude shorter than the length of the day, smaller than Earth's diameter, and weaker than the gravity itself, respectively.



lower noise levels on the ground. In addition, hybrid systems combining the benefits of quantum accelerometers with electrostatic accelerometers, which still provide higher measurement rates, could cover a wider range of slower and faster accelerations and could greatly support navigation and inertial sensing on the ground and in space. Quantum accelerometers will also serve as a basis for developing the next generation of gravity-monitoring missions, such as the follow-on to the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission, which will measure gravity differences in 3D and allow higher-resolution mapping of Earth's static gravity field.

Wide-Ranging Improvement

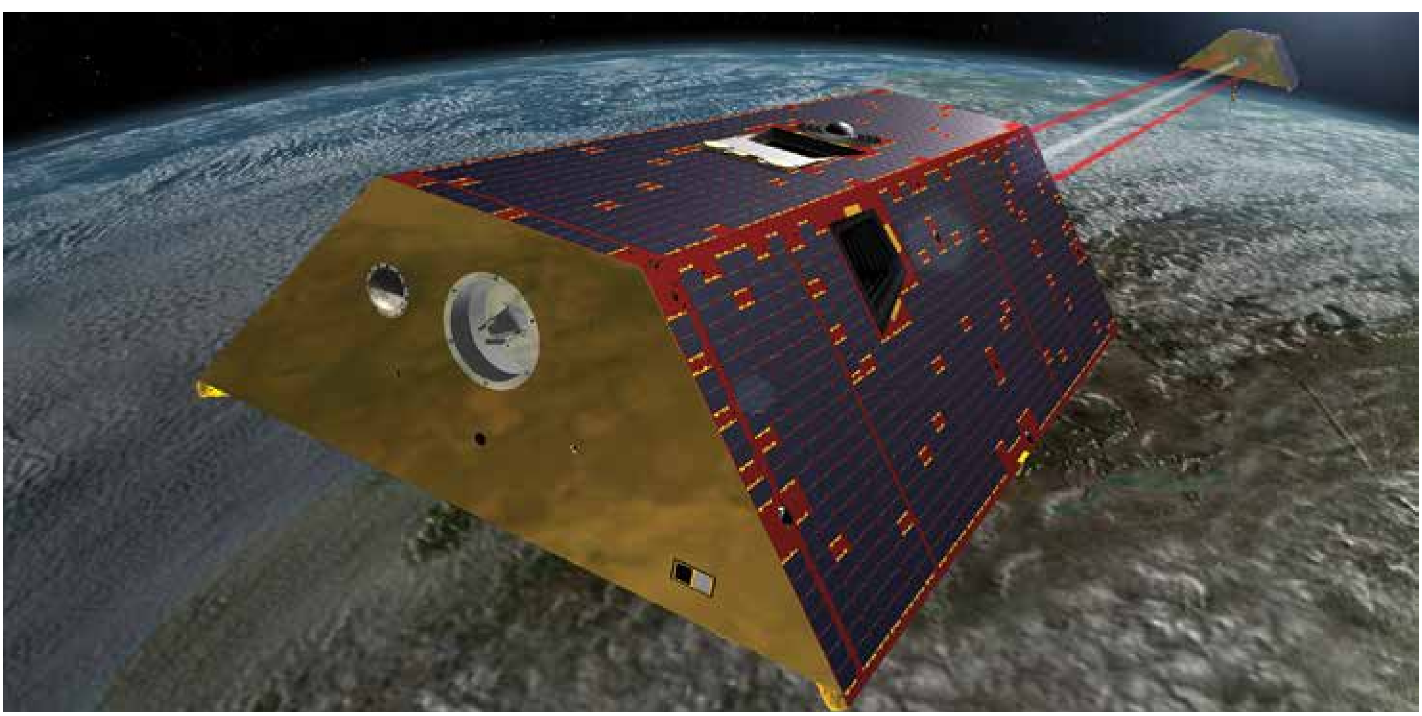
The second pillar of QuGe focuses on improving technology for laser interferometric ranging between spacecraft to achieve nanometer-scale accuracy, which will become the standard for future geodetic gravity-sensing missions. This method involves comparing the difference in phase between two laser beams: a reference beam and a test beam received back from the second satellite. Such optical measurements are much more precise than similar measurements using microwave ranging or mechanical devices, allowing intersatellite distances to be observed with an accuracy of tens of nanometers or better compared with micrometer accuracies achieved with microwaves.

High-precision laser ranging was successfully tested in 2017 during the Laser Interferometer Space Antenna (LISA) Pathfinder mission, in which the main goal was to hold the spacecraft as motionless as possible to test technology for use in future missions that will seek to detect gravitational waves with a space-based observatory. It has also been applied successfully in the GRACE-FO mission, demonstrating the superior performance for intersatellite tracking of laser interferometry over traditional microwave-based ranging methods used in the original GRACE mission.

The current GRACE-FO mission has demonstrated the superior performance for intersatellite tracking of laser interferometry over traditional microwave-based ranging methods.

Although extremely useful, recent satellite gravity missions give only rather rough pictures of global mass variations. Enhanced monitoring of intersatellite distances should improve the ability to resolve 1-centimeter EWH to about 200 kilometers or finer, instead of the 400 kilometers presently. This improvement will allow better separation of overlapping effects, such as continental versus oceanic mass contributions along coastlines, changes in neighboring subsurface aquifers, and variations in glaciers and nearby groundwater tables.

Even more refined concepts, like intersatellite tracking using laser interferometry for multiple satellite pairs or among a swarm of satellites, might be realized as well within the coming years. Using more satellites in next-generation geodetic missions would yield data with higher temporal and spatial resolution and accuracy—and hence with greater ability to distinguish smaller-scale processes—than are available with current two-satellite configurations.



The Grace-FO mission, a joint NASA-GFZ (German Research Centre for Geosciences) project, illustrated here in orbit above Earth, has demonstrated high-precision laser ranging interferometry for intersatellite tracking. Credit: NASA/JPL-Caltech

The transportable optical clock of the Physikalisch-Technische Bundesanstalt (PTB), the National Metrology institute of Germany (left) is housed inside a trailer (right). Credit: PTB Braunschweig, CC BY 4.0 (bit.ly/ccby4-0)

Measuring Height with Optical Clocks

QuGe's third pillar of development focuses on applying general relativity and optical clocks to improve measurement reference systems. Einstein told us that gravity distorts space and time. In particular, a clock closer to a mass—or, say, at a lower elevation on Earth's surface, closer to the planet's center of mass—runs slower than one farther away. Hence, comparing the ticking rates of accurate clocks placed at different locations on Earth informs us about height differences, a technique called chronometric leveling. This technique has been achieved by comparing outputs from highly precise optical clocks connected by optical links over distances on the order of 1,000 kilometers.

Today systems for measuring height are referenced to mean sea level in some way, for example, through tide gauges. However, sea level is not stable enough to be used as a reference.

Optical clocks keep time by measuring the high frequency of a laser light that is kept locked to the transition frequency between two given energy levels of electrons in ultracold (laser-cooled) atoms or ions. These clocks have demonstrated at least a 100-fold improvement in accuracy over the usual atomic clocks, which measure lower-frequency microwave transitions. With a global network of such optical clocks, if we can remotely compare the clocks' frequencies with the same accuracy, we could realize a global height reference with 1-centimeter consistency. One can even imagine the reference clocks being placed in a high satellite orbit, far from the noisy Earth environment, to serve as a stable reference for terrestrial height systems and improve measurement accuracy.

In addition to chronometric leveling, such clocks will improve the accuracy of the International Atomic Time standard—the basis for the Coordinated Universal Time used for civil timekeeping—and will have many other impacts on science and technology. For example, global navigation satellite systems could provide better navigation by using more predictable clocks on satellites, which would have the added advantage of requiring less input from the ground operators controlling the satellite orbits. Space navigation could rely on one-way range measurements instead of on more time-consuming two-way ranging if a spacecraft's clock were highly accurate. And radio astronomers could make use of more stable frequency references for easier processing and better results in very long baseline interferometry experiments. More fundamental applications are also envisioned for optical clocks, such as detecting gravitational waves, testing the constancy of the fundamental constants of physics, and even redefining the second.

The Best Tools for the Job

Our knowledge of Earth's shape and gravity and the subtle shifts they undergo in response to numerous natural and human-induced processes has grown immensely as geodetic methods and tools have matured. But with current technologies, the clarity and confidence with which we can discern these changes remain limited. Such limitations, namely, insufficient accuracy and resolution in time and space, will become increasingly important as we look to better understand and predict the consequences of accelerating—or even perhaps previously unrecognized—changes occurring as the planet responds to warming temperatures and other anthropogenic influences.

The future of high-precision geodesy lies in the development and application of novel technologies based on quantum mechanics and relativity. QuGe is working to ensure that the Earth and planetary sciences benefit from the vast potential of these technologies. In particular, ultracold-atom accelerometry, high-precision laser ranging between satellites, and relativistic geodesy with optical clocks are very promising approaches that will overcome problems of classical gravimetric Earth observations. With such advances, we will have the best tools available not only to understand vital geophysical processes but also to better navigate on Earth and in space and to discern the fundamental physics that underlie our world.

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The Cormorant Oceanography Project is using sensors deployed on diving marine birds to collect oceanographic data in coastal regions around the world.

Double-crested cormorants drift around their nesting colony on East Sand Island near the mouth of the Columbia River, on the border of Oregon and Washington, in 2012. Credit: Adam Peck-Richardson

CORMORANTS ARE HELPING CHARACTERIZE COASTAL OCEAN ENVIRONMENTS

By Rachael A. Orben, Adam G. Peck-Richardson, Greg Wilson, Dorukhan Ardağ, and James A. Lerczak

The coastal ocean is an extraordinarily energetic place where water and sediments are always in motion. More than a third of the human population lives near coastlines globally, and we are collectively dependent on the coastal ocean for subsistence, commerce, and recreation. Rising sea levels and increasing intensity of storms are just two consequences of climate change that are influencing and will continue to influence the dynamics of coastal ecosystems. It is

Cormorants roost on a channel marker in the Columbia River estuary in Oregon. Backpack-style biologging devices on two of the birds (left and second from right) measure the dynamic oceanographic features the birds encounter on their daily foraging dives. Credit: Adam Peck-Richardson

these dynamic physical characteristics and important mutual influences that make the coastal ocean critical to study but equally challenging to observe.

Oceanographers who study coastal ocean processes face a cost-benefit trade-off when planning sampling efforts. Surveys from oceanographic vessels provide opportunities to take measurements over broad areas, but time constraints, ship costs, and vessel drafts limit surveys. In contrast, instruments mounted on moorings can measure long-term time series, but only at discrete strategic locations. Autonomous underwater vehicles (AUVs) offer a mobile and continuous sampling approach, but they are expensive to deploy and maintain, and strong currents, waves, and salinity gradients can reduce maneuverability or prohibit sampling through exceptionally dynamic regions.

Biologging—attaching miniature sensors to animals—is an emerging method for making long-term, low-cost, and widely distributed autonomous measurements of the environment [*Biuw et al.*, 2007; *Harcourt et al.*, 2019]. Marine animals like seabirds and seals often access hard to sample locations, and they do so under their own power. Advances in data transmission and sensor technologies are facilitating the development of miniaturized biologging devices that can make oceanographic measurements and are suitable for small diving marine animals like seabirds.

Insights into Marine Bird Ecology

Cormorants, which forage in biologically rich nearshore areas, can be used as indicators of ecosystem health. In particular, cormorants tend to follow boom-bust cycles that track the availability of the fish they eat. Yet the specific ecological role of many cormorant species is unclear.

Like other predators, cormorants are often viewed as being in direct competition with humans, and they are vilified, persecuted, or simply ignored. The animal movement data collected through the Cormorant Oceanography Project, in tandem with oceanographic data, provide important basic information on the birds' foraging ecology, distributions, and migrations. This information, in turn, is valuable for efforts such as marine spatial planning, in which human activities are coordinated to balance demands for development with the need to protect the environment.

Oceanographic Measurements from Cormorants

The Cormorant Oceanography Project, initiated in 2013, is advancing biologging tag technologies for use with cormorants to measure in situ oceanographic conditions. Cormorants and shags make up a family (Phalacrocoracidae) of about 40 species of birds that inhabit coastal oceans and inland waterways from the tropics to high latitudes. Marine cormorants typically forage along the seafloor at depths of up to 80 meters, and they can make more than 100 dives each day. Between dives, cormorants rest on the sea surface, so their movements allow both water column and surface conditions to be measured with biologging.

The biologging tags we currently use are equipped with small, low-power, fast-response sensors to measure water temperature, conductivity (for water salinity levels), and pressure (for water depth). Each tag also features an inertial measurement unit (IMU) to monitor acceleration and orientation. A GPS unit, triggered when a bird surfaces, provides locations for georeferencing measurements, and solar cells recharge the tags' batteries (at the time of writing, some tags have been transmitting continually for more than 2 years). The sensors collect large volumes of data that are transmitted and retrieved using two-way cellular communications. Cellular communications also allow us to transmit new sampling programs to the tags (Figure 1).

We are processing tag sensor data to obtain fundamental information about vertical temperature and salinity profiles, bottom soundings (which measure bathymetry), surface currents, surface gravity wave statistics (which characterize wave motions at the water-air interface), and air-sea temperature contrasts (which help us to understand ocean-atmosphere coupling). The data provide measurements from unsampled dynamic coastal marine environments, allowing us to correct uncertainties in boundary conditions and parameters of ocean models and thus to improve model predictions in a process known as data assimilation.

Processing bottom soundings obtained from pressure records gathered during cormorant dives requires disentangling bird behavior from the data. For example, we use dive shape to distinguish benthic (seafloor) dives from those to intermediate depths, which reduces uncertainty in the bottom sounding data.

For information about surface currents and surface gravity wave statistics, we use consecutive GPS fixes and high-frequency IMU measurements. Compiling this environmental information requires using the IMU data to distinguish active bird behavior (e.g., flying and paddling) from drifting passively on the ocean surface.

Measuring well-resolved temperature and salinity profiles is theoretically straightforward with data from diving birds, although engineering challenges remain. These challenges include designing a sensor housing that produces temperature measurements with a short response time and developing a small conductivity sensor that produces stable measurements for the duration of tag deployments. We are working with tag manufacturers to iteratively develop and test tag

and sensor prototypes to improve profile measurement capabilities.

Finally, contrasts in air and sea temperatures can theoretically be measured at the beginning of dives when birds first submerge and at the end when they surface. Precisely measuring air temperature is more challenging than measuring water temperatures, however, so improving determination of these contrasts is a long-term goal of the project.

Outfitting Cormorants in the Columbia River Estuary

In summer 2019, we fit 22 Brandt's cormorants (*Phalacrocorax penicillatus*) captured from roosting sites near the mouth of the Columbia River, on the Oregon-Washington border, with biologging tags using backpack-style harnesses. At about 40 grams, these tags weighed less than 3% of a cormorant's body mass, minimizing effects on the birds' normal activities [*Fair et al.*, 2010].

Brandt's cormorants are fish-eating, foot-propelled pursuit divers—meaning that they chase prey—and are endemic to the California Current, a coastal ocean current flowing between British Columbia and Baja California. We found that Brandt's cormorants are generally loyal to their roosting sites and foraging areas. The Columbia River estuary was their core habitat during the summer, but individual birds moved both north and south. Thus, our tagged birds collected concentrated data near the mouth of the river as well as along much of the Pacific coast of North America (Figure 2a), diving as far as 79 meters below the sea surface. This study allowed us to try out various tag types and collect oceanographic data to use in an assimilative model within a well-studied and highly dynamic estuary system (Figure 2b).

THE DATA PROVIDE MEASUREMENTS FROM UNSAMPLED DYNAMIC COASTAL MARINE ENVIRONMENTS, ALLOWING US TO IMPROVE MODEL PREDICTIONS.

Because of the birds' autonomy in where and when they dive, the data they collect are heterogeneously distributed, making it difficult to interpret oceanographic information with analysis methods that require regular sampling intervals (e.g., averaging data over a long time at one location or performing a spectral analysis on a time series of data). Instead, we are applying techniques from inverse modeling and data assimilation and are using a numerical ocean model to fill gaps between data points and to infer ocean properties not directly observed.

For example, we are inferring seafloor bathymetry from our biologging data. Coastal bathymetry is often poorly known, and it is always changing. The mouth of the Columbia River is continually being filled in with sand, which forms unpredictable shoals and channels [*Stevens et al.*, 2020], and annual dredging operations remove at least 1.5 meters of sediment from navigational channels to keep them safe for commercial shipping. The ability to estimate bathymetry from frequent, autonomous biologging measurements thus may have a practical utility for safe ship navigation and channel maintenance.

Instead of trying to determine the shape of the seafloor directly from the scattered data coming from the cormorants, we apply data inversion. First, we consider various model seafloor profiles using a method developed by *Evensen* [2009], in which a sample of randomly generated candidate bathymetries is run through a numerical model to obtain a least squares–based statistical relationship between these bathymetries and the observational surface current data [*Wilson et al.*, 2010]. Then this relationship can be inverted (back-calculated) to estimate the bathymetry that best fits the real data.

We are currently testing this inverse approach for use with distributed biologged measurements of surface currents. In the future, we may use similar techniques to determine parameters other than bathymetry, such as the strengths of cold-water currents that upwell from the depths of coastal oceans, for which we could make use of temperature data collected by the cormorants.

Upgrading Tag Technology

Although the tags we have used to date have proven effective, continued advances in tag attachment methods, targeted sampling (recording data when birds are foraging or resting on the sea surface), and battery miniaturization, as well as in tag solar panels, sensors, electronics, and communications, would help to optimize biologging devices for improved data collection and for use with different species.

Biologging tags should be as small as possible relative to the mass of the animals carrying them, and they should be positioned to have negligible impacts on the animals' energy expenditure as they fly or dive. Whereas high-latitude cormorants, including Brandt's, tend to have larger bod-

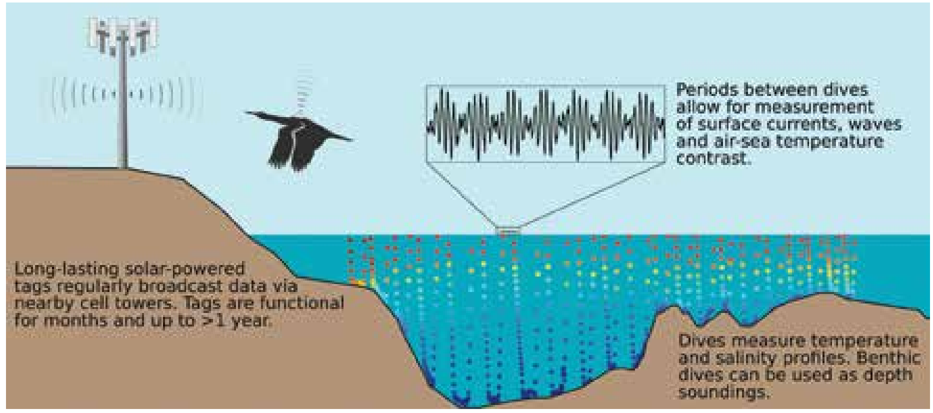

Fig. 1. The Cormorant Oceanography Project uses two-way cellular communications with biologging tags to relay data. While foraging, cormorants make consecutive dives and collect vertical profiles of temperature and salinity, and they provide depth soundings. GPS readings and accelerometer data collected between dives, when birds rest and drift on the surface, provide measurements of surface current velocity and surface gravity waves. Colored dots show water temperature data collected by a diving cormorant in the Columbia River estuary in 2019, where temperatures ranged from about 11°C near the bottom to 19°C at the surface. The data inset shows vertical velocity measured by an accelerometer in a tag deployed on a floating bird decoy in the O. H. Hinsdale Wave Research Laboratory at Oregon State University. Credit: Vexels (flying cormorant image)

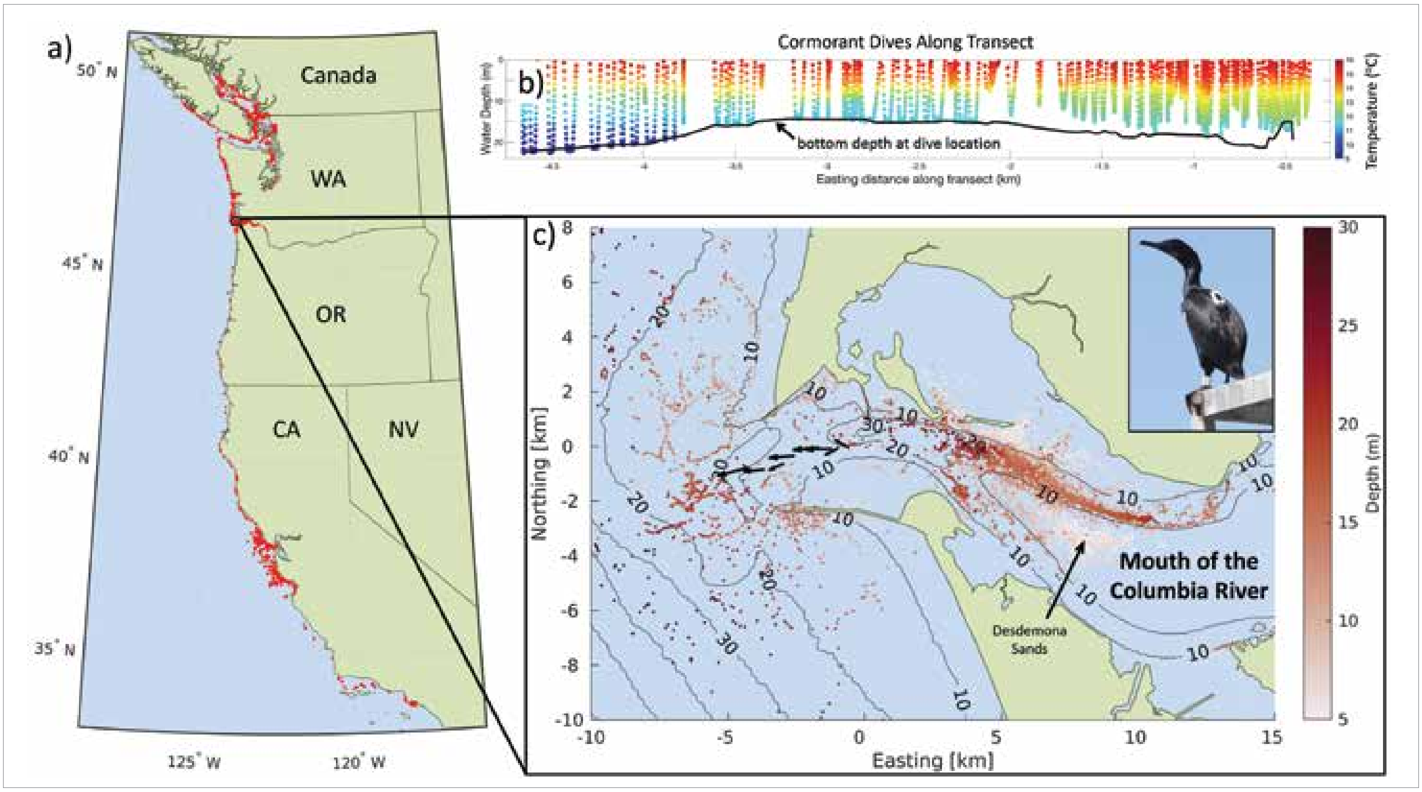

Fig. 2. (a) Cormorants tagged at the mouth of the Columbia River (near the Washington-Oregon state line) traveled long distances along the Pacific coast. About 325,000 dives by these birds (red dots) have been recorded to date. (b) Transect of temperature profiles (color-coded dots) collected by a bird at the mouth of the Columbia River during an ebbing tide over a period of about 1.8 hours. The bird reached the bottom at easting distances less than −2.2 kilometers. (c) Locations of water column profiles, color-coded by maximum dive depth, collected by tagged Brandt's cormorants (inset) at the mouth of the Columbia River. Arrows indicate surface current velocities (the maximum shown here is 1.1 meters per second) estimated from the tagged birds, drifting at the surface between dives, along the transect shown in Figure 2(b). Credit: Adam Peck-Richardson (inset); National Geophysical Data Center (bottom depth and bathymetric contours).

ies (2.5 kilograms), tropical cormorants can be as small as 360 grams, necessitating further tag miniaturization.

Furthermore, although the use of cell phone technology allows tags to transmit large amounts of data, data transmission is possible only in locations with cell phone coverage. The tags also require occasional electronic updates to keep up with consumer-driven advances in cellular technologies (e.g., 5G).

WE WILL USE TAG DATA FROM SOCOTRA CORMORANTS IN THE ARABIAN GULF TO DIAGNOSE SEA SURFACE TEMPERATURE BIASES THAT OCCUR IN MODELS.

Finally, considering the birds' autonomy, the biologging data they collect pose challenges to coordinating near-real-time data processing, archiving, and distribution. Maintaining data provenance, including measures of uncertainty associated with behavioral biologging data (as distinct from uncertainties in data obtained by conductivity-temperature-depth instruments), requires flexibility that has yet to be built into many oceanographic data repositories.

A Work in Progress

Since 2019, we have collected more than half a million dive profiles from three species of cormorants foraging in a range of near-shore habitats (Figure 3): In addition to the Brandt's cormorants from the Columbia River estuary, we have fit biologging tags to pelagic cormorants to study the water near Middleton Island, Alaska, and to Socotra cormorants in the Arabian Gulf off the United Arab Emirates. We are now evaluating these data and comparing them with numerical models.

Among other findings, these comparisons have revealed errors in models of temperatures for deep, cold ocean water that upwells to the surface, a common source of uncertainty in regional-scale ocean models on the U.S. West Coast. Future work will investigate other uncertainties about how coastal ocean environments function. For instance, we will use tag data from Socotra cormorants in the Arabian Gulf to diagnose sea surface temperature biases that occur in models and that are commonly associated with uncertain atmospheric forcing (e.g., the influence that dust storms exert on incoming shortwave radiation) [*Lorenz et al.*, 2020].

Although we have made much progress in tag development, our near-term goals are to improve the response times of the temperature sensors we use, to test and improve our conductivity sensors, and to put smaller versions of these tags through trials. Over the next couple of years, we also aim to scale up our tag deployments through international collaborations and through the development of a global cor-

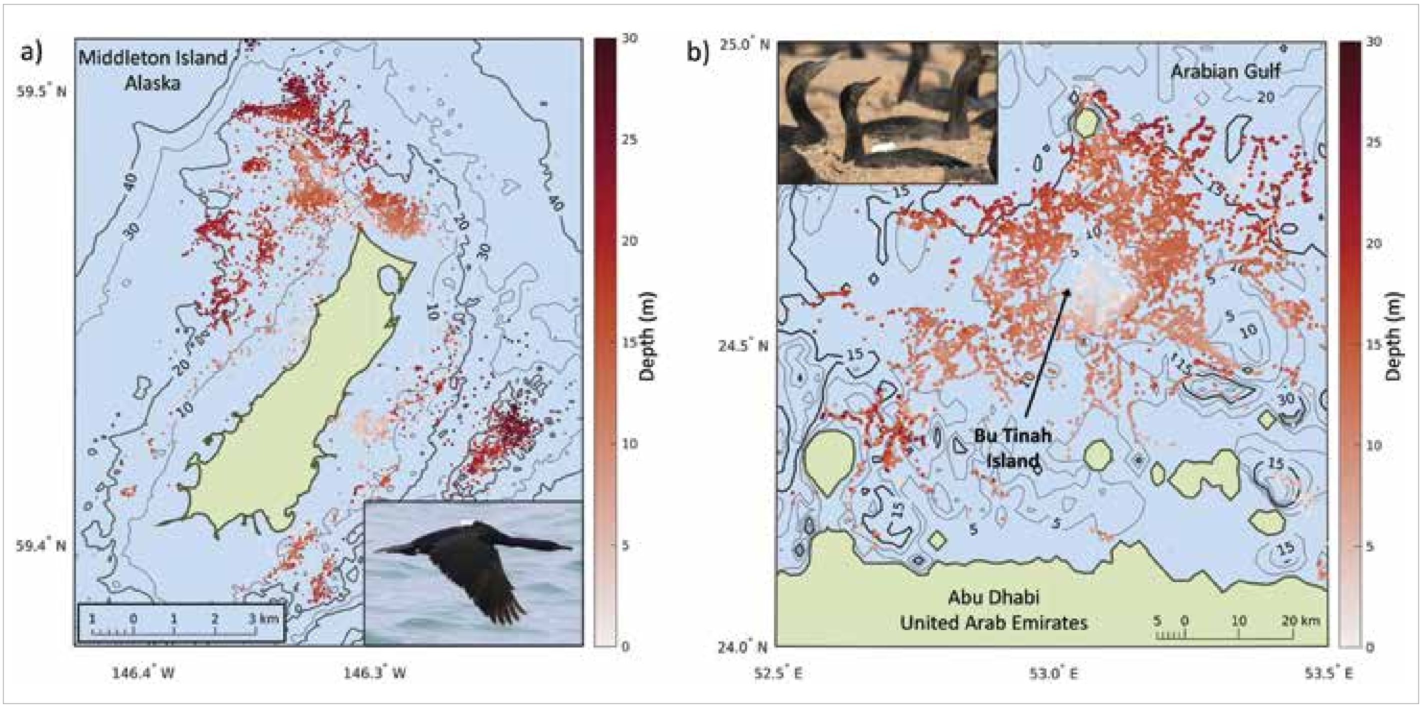

*Fig. 3. Dive depths from biologging cormorants are indicated here by color-coded red dots, with species photos shown in the insets. (a) Eighteen pelagic cormorants (*P. pelagicus*) made 71,407 nearshore dives during a 2-week deployment near Middleton Island in the Gulf of Alaska in July 2020. (b) Eleven Socotra cormorants (*P. nigrogularis*) made 30,611 dives in the Arabian Gulf between November 2020 and January 2021. Credit: (a) Google Earth (shoreline), NOAA (bathymetry), Brendan Higgins (inset photo); (b) NOAA (bathymetry), Sabir Bin Muzaffar (inset photo)*

morant oceanography network. Furthermore, we are building an automated data pipeline through the Animal Telemetry Network to provide our biologging data to the oceanographic research community in near-real time.

With these efforts, we are continuing to expand the range of techniques and data that scientists have at their disposal to better understand highly dynamic—and highly important—coastal ocean environments.

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Earthly Lava Tubes May Offer Insights into Extraterrestrial Life

Researchers used lava tubes at Lava Beds National Monument as analogues for caves that may exist in other parts of the solar system. Credit: Brian Anschel

Since 1997, NASA has successfully landed five rovers on Mars. The rovers have beamed back data that indicate life cannot survive on the Martian surface; we do not know whether life persists below the ground, however. For subterranean life to endure on Mars or elsewhere, microbes would have to convert—or fix—elements from their inorganic form into a usable organic form. This skill, known as lithoautotrophy, comes in handy for Earth-bound bacteria, too—specifically for microbes living in caves, which often lack nutrients because of the absence of sunshine and organic material enjoyed by life on the surface.

In a new paper, *Selensky et al.* try to move us closer to understanding whether underground extraterrestrial life could exist by exploring carbon cycling in the lava caves at Lava Beds National Monument in California. As lava flows from a volcanic eruption, a stiff outer shell eventually solidifies as magma continues to flow inside, creating hollow tubes. Because lava tubes form through volcanism, they are presumed to exist elsewhere in the solar system, making them valuable models for planetary speleology.

In California, the authors examined the carbon sources used by cave bacteria living in biofilms (colorful microbial communities on the cave walls), speleothems, and soil. They compared carbon isotope signatures in bacterial fatty acids to carbon sources outside the cave.

The researchers found that the fatty acids produced by Actinobacteria in biofilms bear isotope signatures that could not derive from outside sources. In other words, the bacteria are fixing carbon in situ. In contrast, bacteria from other cave features, such as the speleothems, assimilate organic carbon derived from the surface.

The results suggest that some bacteria in basaltic cave ecosystems are fixing their carbon, which indicates that the microbes survive independent of the surface environment. The findings challenge the paradigm that all cave microbiota subsist on surface inputs. Furthermore, the authors say the conclusions have significant and positive implications for the search for extraterrestrial life. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006430, 2021) **—Aaron Sidder,** *Science Writer*

Understanding Tremors Through Tree Rings

When trying to make sense of past earthquakes, researchers typically turn to the geological record. However, there may be clues to understanding old quakes in the biological record as well—in tree rings, for example. As earthquakes shake Earth's surface, they increase the permeability of soils, potentially shifting the flow of water underground. Previous observations suggest that after a quake, water may gather in valleys and drop along ridges, which could affect tree growth and transpiration, particularly in water-stressed environments.

To test this, *Mohr et al.* looked at pine forest plantations on the Chilean Coastal Range after the Maule earthquake in 2010. The magnitude 8.8 quake increased streamflow and evapotranspiration for at least 10 days. The team used core samples of trees located on the valley floor and the hillslope ridges and looked at highly resolved subseasonal stable isotope ratios of tree rings to understand the growing season conditions—a reflection of the hydrological response to the earthquake. In a first, the authors also considered cell-level wood anatomy, quantifying features of the tree rings, including the lumen area (the space inside the circular tree ring structure), lumen diameter, cell wall thickness, and cell diameter, to understand how the hydrological changes may have affected tree response to the quake in terms of the conductivity of wood for water and tree growth.

Although the impacts were small, the authors conclude that the postseismic changes in water availability did influence tree growth and photosynthesis. The data show that evapotranspiration increased in the valleys and decreased along the ridgelines. Because no rain fell in the period leading up to the earthquake, these changes were likely induced by earthquake-triggered changes in water availability.

The authors caution that these kinds of responses are likely to occur only in environments with limited water availability, where earthquakes may provide extra water that relieves water stress. The study shows how a dendrohydrological analysis over the short term (i.e., on the scale of weeks) can pick up on impacts that annual-scale analyses might miss. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006385, 2021) **—Kate Wheeling,** *Science Writer*

Irtysh River Drove Arctic Sea Ice Expansion 3 Million Years Ago

During the late Pliocene, Arctic sea ice began to expand rapidly. The new ice created changes in sea level, albedo, thermohaline circulation, and a host of other factors that still drive the planet's climate today. But piecing together what caused the ice to expand rapidly has remained an elusive goal for scientists.

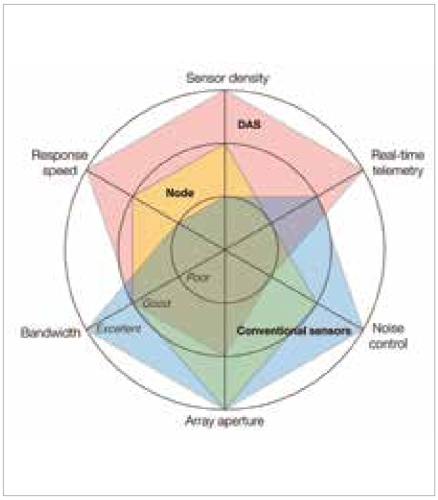
Now a new study by *Ma et al.* shows that the sea expansion coincided with the formation of Siberia's Irtysh River 2.77 million years ago. Previous work has shown that the Irtysh River was once a series of inland rivers that drained into a large paleolake in the Junggar Basin, located in northwestern China. But at some point, the basin burst, and the Irtysh began to flow northward toward the sea.

The Irtysh River flows through Omsk, Siberia, Russia. Credit: Petar Milošević, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

By analyzing neon-21 isotopes along with aluminum-26/beryllium-10, the researchers determined the timing of this critical event. Isotopes like these can be used to date rock and sediment samples because they are cosmogenic in nature and decay at different rates, meaning that if a sample is exposed to cosmic rays at the surface, the isotopes will be created. If the sample is then buried, the different nuclides will decay at different rates, providing insight into how long the sample has been sequestered from cosmic rays. With this technique, the scientists reconstructed much of the Junggar Basin's geologic history and inferred when the Siberian-Arctic river system began supplying fresh water to the Arctic Ocean.

The new water provided by the Irtysh created a layer of fresh water roughly 9 meters thick in the Kara Sea, which lies off of western Siberia. The scientists say this sudden influx of fresh water would have disrupted the vertical stability of the water and reinforced the stratification of vertical circulation. In combination, these changes created more sea ice in the Arctic, which then drove a series of albedo-based feedbacks, creating colder temperatures and yet more ice. The results show what an incredible impact even a single freshwater input can have in driving sea ice formation and the planet's climate at large. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL093217, 2021) **—David Shultz,** *Science Writer*

Aftershocks and Fiber Optics

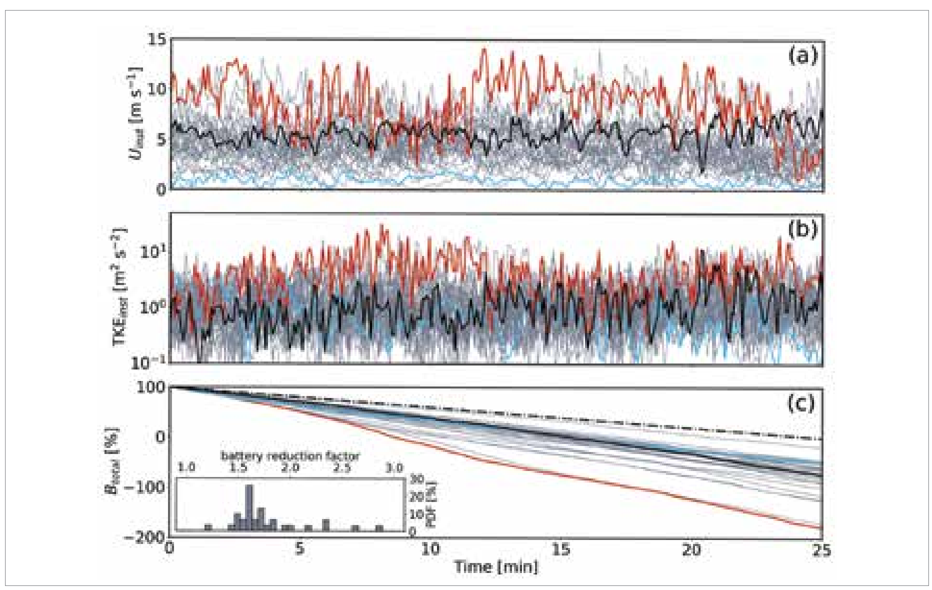


In recent years, technological advances have led to new types of seismological measurement strategies for both academic and industry applications, including those that allow for very dense ("large N") sensor deployments. In particular, existing fiber-optic cables, such as those used for Internet communications, can be transformed into strings of thousands of quasi-seismometers along many kilometers of cable. *Li et al.* show the promise of such distributed acoustic sensing (DAS) in a rapid response setting, where an objective might be to record seismic activity after an earthquake. By connecting a cable interrogation unit—which interprets signals in fiber-optic cable—to a single strand of existing fiber near the magnitude 7.1 Ridgecrest earthquake in 2019, the authors dramatically increased the number of recorded aftershocks compared with the number recorded by conventional detection methods. This demonstration illustrates the potential for DAS to complement permanent seismometer networks and to allow researchers to zoom in on fault zone structure and dynamics at unprecedented levels of detail. (https://doi.org/10.1029/2021AV000395, 2021) **—Thorsten W. Becker**

Complementary strengths and weaknesses of three classes of seismic instrumentation—conventional seismic sensors, nodal sensors, and distributed acoustic sensing (DAS)—used for earthquake response. Credit: Li et al.

Modeling Urban Weather Effects Can Inform Aerial Vehicle Flights

New technologies for aerial operations, collectively known as Advanced Air Mobility (AAM), are emerging for use in urban environments. Initial testing and demonstration exercises of these technologies, which include electrically propelled vertical takeoff and landing aircraft for infrastructure surveillance, goods delivery, and passenger transportation, are planned for the very near future. To enable safe and efficient deployment of these new aerial operations, the meteorological community must provide relevant guidance on weather and turbulence in urban environs. *Muñoz-Esparza et al.* demonstrate how seasonal, diurnal, day-to-day, and rapidly evolving sub-hourly meteorological phenomena create unique wind and turbulence distributions within the urban canopy. They also showcase the potential for efficient ultrafine-resolution atmospheric models to understand and predict urban weather impacts that are critical to AAM operations. (https://doi.org/10.1029/2021AV000432, 2021) **—Donald Wuebbles**



These time series show the simulated (a) wind speed U_{inst}, (b) turbulence kinetic energy TKE_{inst} and (c) battery drainage B_{total} due to elevated turbulence conditions experienced by a small unmanned aerial vehicle (UAV) with a constant speed of 1 meter per second m s^{-1} traveling over downtown Dallas in January 2018. Each curve (gray) in the three plots corresponds to conditions at 12:00 p.m. local time on one of the 31 days that month. The red curve indicates the maximum TKE day (11 January), the blue curve indicates the minimum TKE day (6 January), and the black curve indicates the representative (most likely) weather for that month and time of day (19 January). The black dash-dotted line in (c) is the reference for weak turbulence that would require no additional power to overcome and that would last for a 25-minute flight. The distribution of battery reduction factors is displayed at the bottom left portion of (c). Credit: Muñoz-Esparza et al.

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Multiple Faculty and Research Positions Available in the College of Urban & Environmental Sciences

Positions:

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Description:

— **Department of Environmental Science**

Discipline: carbon cycling, climate change – energy – multi-compartment environment nexus, and physical/chemical/health processes of environmental pollution.

Please contact **Dr. Dongqiang Zhu at zhud@pku.edu.cn.**

— **Department of Physical Geography and Natural Resources**

Discipline: hydrology, soil science, geomorphology, climate change, paleoclimate, ecosystem service, natural resource management, remote sensing, GIS, land-atmosphere interaction, integrated geography, sustainability science and earth system science.

Please contact **Dr. Shushi Peng (speng@pku.edu.cn) and Dr. Jian Peng (jianpeng@urban.pku.edu.cn).**

— **The Institute of Ecology**

Discipline: microbial ecology, biodiversity and conservation biology, evolutionary biology, restoration ecology, landscape ecology and molecular or physiological ecology.

Please contact **Dr. Zhiheng Wang (zhiheng.wang@pku.edu.cn) and Ms. Bei Zhou (zhoubei@pku.edu.cn).**

Phone Number: +86-10-6276-0150.

Required Qualifications:

Applicants must hold a PhD degree in above fields, preferably with at least 2 years of post-doctoral experience, cross-discipline research capability, and teaching experience. Successful candidates should have excellent research background.

Remuneration:

Each position comes with a competitive annual salary and benefit packages.

Required application materials:

(1) curriculum vitae with a complete publication list, (2) statement of research interests, (3) statement of teaching experience and interests, (4) contact information of at least three references (indicate in the cover letter including name, title, affiliation, official e-mail and phone).

EPFL Empa

Faculty Position in Environmental Sensing Technologies

Joint Appointment between the Swiss Federal Laboratories for Materials Science and Technology (Empa) and the Ecole polytechnique fédérale de Lausanne (EPFL)

EPFL's School of Architecture, Civil and Environmental Engineering (ENAC) and the Swiss Federal Laboratories for Materials Science and Technology (Empa) invite applications for a tenured (Associate or Full) Professor in the Institute of Environmental Engineering. The appointee will participate in Empa's Functional Materials Department, and contribute to research and teaching activities within the EPFL Institute of Environmental Engineering.

The Institute of Environmental Engineering (IIE) in ENAC carries out basic and translational research spanning fundamental understanding of environmental systems and their resilience to design of adaption strategies. It covers a diverse portfolio in research, teaching and innovative technology development across transversal themes: understanding and adapting to climate change, distributed and dynamic environmental sensing, resource quality and its effects on ecosystem health, and human-environment interactions.

Empa's Functional Materials Department develops in highly interdisciplinary teams sustainable material and technology solutions for a climate-neutral society, as well as novel soft robotic systems for infrastructure maintenance and environmental monitoring.

The joint Empa/EPFL professor in Environmental Sensing Technologies will have acknowledged strengths in research and innovation related to sensing of relevant variables in water, soil or the atmosphere, as well as leveraging the resulting data for improved environmental sustainability and adaptation. We welcome a range of applications, from environmental specialists who leverage sensing technologies to mobile sensing specialists with interests in environmental questions. Areas of interest within these domains include, but are not limited to:

- Distributed and local sensing of (new) environmental variables via novel methodologies/technologies
- Multi-environment sensing of spatially and/or temporally varying phenomena using mobile platforms
- Integration of sensing with localization, estimation and optimization across multiple scales and terrains (air/soil/water)
- Unconventional sensing (e.g., combining living organisms and mechatronics)

The Empa/EPFL professor will lead an internationally recognized research program that leverages the opportunities offered by Empa and EPFL in cross-institutional, complementary research groups. The appointee will promote excellence in research and in undergraduate and graduate level teaching.

EPFL is a growing and well-funded institution with excellent experimental and computational infrastructure. Teaching and research at EPFL covers essentially the entire palette of engineering and science, and offers a fertile environment for research collaboration between different disciplines. Empa conducts cutting-edge research for the benefit of industry and the well-being of society. The EPFL and Empa environments are multilingual and multicultural, with English serving as a common interface.

The following documents are requested in PDF format: cover letter including a statement of motivation, curriculum vitae, publications list, concise statements of research and teaching interests, as well as the contact information of at least five references who are ready to supply their letter upon request.

To apply, please follow the application procedure at:
https://facultyrecruiting.epfl.ch/position/35848192

Formal evaluation of the applications will begin on **15 January 2022** and the search will continue until the position is filled.

Further enquiries should be made to:
Prof. Athanasios Nenes
Chair of the Search Committee
E-mail: SearchEnvSensingTech@epfl.ch

Additional information on Empa:
Dr. Tanja Zimmermann (tanja.zimmermann@empa.ch)
Head of Department Functional Materials

Additional information on Empa and EPFL: https://empa.ch, https://www.epfl.ch

EPFL and Empa are equal opportunity and family friendly employers. We are committed to increasing the diversity of their faculty, and strongly encourage women to apply.

From the North Atlantic, bobbing in the Norwegian Sea, the scientists of International Ocean Discovery Program (IODP) Expedition 396 send their greetings! Off the decks of the *JOIDES Resolution*, we're drilling into the seafloor thousands of meters below the sea surface with the hope of solving a decades-old climate mystery: What caused the last major global warming event, the Paleocene-Eocene Thermal Maximum (PETM)?

One leading theory proposes that the PETM was caused by a short burst of intense volcanic activity in between what are now Iceland and Norway. Huge flows of magma in the region might have released methane from organic materials in overlying sediment layers, which could have spiked global carbon dioxide levels and contributed to raising global atmospheric temps by 5°C–8°C.

By studying core samples of igneous and sedimentary rocks, the scientists hope to figure out just how this period of volcanic activity was linked to the PETM. The data collected will also help us understand the future facing Earth as we experience a similar, albeit human-caused, warming.

Follow our expedition on Twitter (@TheJR) and Instagram (@joides_resolution), and learn more about the ongoing science at our blog (bit.ly/joides-resolution-expedition).

—**Mara Johnson-Groh,** *JOIDES Resolution* team

Photo by Peter Betlem

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